From DEPARTMENT OF CLINICAL NEUROSCIENCE
Karolinska Institutet, Stockholm, Sweden

# INVESTIGATIONS OF BINOCULARITY AND READING PERFORMANCE IN HEALTHY SUBJECTS AND PATIENTS WITH MILD TRAUMATIC BRAIN INJURY

Jan Johansson

Stockholm 2015

All previously published papers were reproduced with permission from the publisher.
Published by Karolinska Institutet.
Printed by AJ E-print AB

ISBN 978-91-7676-048-2

# INVESTIGATIONS OF BINOCULARITY AND READING PERFORMANCE IN HEALTHY SUBJECTS AND PATIENTS WITH MILD TRAUMATIC BRAIN INJURY

## THESIS FOR DOCTORAL DEGREE (Ph.D.)

By

## Jan Johansson

*Principal Supervisor:*
Associate professor Tony Pansell
Karolinska Institutet
Department of Clinical Neuroscience
Division of Ophthalmology and Vision

*Co-supervisor(s):*
Fil dr Gustaf Öqvist Seimyr
Karolinska Institutet
Department of Clinical Neuroscience
Division of Ophthalmology and Vision

Professor Jan Ygge
Karolinska Institutet
Department of Clinical Neuroscience
Division of Ophthalmology and Vision

*Opponent:*
Professor Kenneth Ciuffreda
State University of New York
College of Optometry

*Examination Board:*
Associate professor Hans Richter
University of Gävle
Department of Occupational and Public Health
Division of Center for Musculoskeletal Research

Professor Lena von Koch
Karolinska Institutet
Department of Neurobiology,
Care sciences and Society
Division of Occupational Therapy

Associate professor Heléne Hamberg-Nyström
Karolinska Institutet
Department of Clinical Neuroscience
Division of Ophthalmology and Vision

To my family

# ABSTRACT

Background: It is known that problems with binocular vision can cause issues for reading, less well known is to what extent binocular vision improves reading performance. A key aim for this project was to estimate the contribution of binocularity in reading in healthy subjects, and in patients with mild traumatic brain injury (MTBI). A second aim was to evaluate the role of eye dominance in reading and the occurrence of graded eye dominance under true binocular viewing conditions. The third and final aim was to evaluate the effect of spectacle treatment on visual function, symptoms and reading performance in patients with MTBI.

Subjects: Papers I and II each included 18 healthy subjects and paper III 32 healthy subjects, all with normal vision. Paper IV included eight patients with a documented history of MTBI who had been referred due to persisting symptoms and vision based issues.

Methods: Reading was done with left, right and both eyes in a balanced repeated measures study design (paper I-II). Continuous text, controlled for readability, was presented at high or reduced contrast. Graded eye dominance was assessed with a binocular sighting test and the Variable Angle Mirror Test (paper III). In paper IV visual symptoms, visual function and reading performance were assessed before and after spectacle treatment.

Results: A marginal binocular advantage occurred at reading of high contrast text. At reduced contrast levels, however, binocular reading speed was significantly faster than monocular. An interaction effect was found between monocular reading and low contrast levels leading to prolonged mean fixation duration. The binocular eye dominance tests showed a weighted balance between the eyes for a majority of subjects. The strength of the weighting (towards either eye) was correlated to the amount of monocular blur required to alter the balance. Spectacle treatment led to symptom reduction and minor improved visual function in some of the patients. The relation between improved reading performance and symptom reduction was inconsistent. Monocular reading resulted in worse reading efficiency and comprehension.

Conclusion: The findings in reading performance parallel the literature where the binocular advantage is small for complex stimuli of high contrast, but increases with reduced contrast levels. The results suggest that binocularity contributes to the robustness of reading performance. Monocular reading performance was generally equal in subjects with normal vision with no clear relation to eye dominance. The results of the binocular dominance tests indicate plausible effects of graded eye dominance affecting how the visual scene is perceived under true binocular viewing conditions. Spectacle treatment can reduce symptoms for MTBI patients but with marginal effects on visual performance.

# LIST OF SCIENTIFIC PAPERS

I. Johansson, J., Pansell, T., Ygge, J., & Seimyr, G. Ö. (2014). Monocular and binocular reading performance in subjects with normal binocular vision. Clinical & Experimental Optometry, 97(4), 341-348.

II. Johansson, J., Pansell, T., Ygge, J., & Seimyr, G. Ö. (2014). The effect of contrast on monocular versus binocular reading performance. Journal of Vision, 14(5), 8.

III. Johansson, J., Seimyr, G. Ö., & Pansell, T. (2015). Eye dominance in binocular viewing conditions. Journal of Vision, 15(9), 21.

IV. Johansson, J., Nygren-de Boussard, C., Seimyr, G. Ö., & Pansell, T. The effect of spectacle treatment in patients with persisting symptoms after mild traumatic brain injury. Submitted for publication.

# CONTENTS

# LIST OF ABBREVIATIONS

| | |
|---|---|
| BPC | Baseline Projection Center |
| BST | Binocular Sighting Test |
| CISS | Convergence Insufficiency Symptom Survey |
| GCS | Glasgow Coma Scale |
| HICT | Hole-In-the-Card-Test |
| IReST | International Reading Speed Texts |
| LE | Left Eye |
| MTBI | Mild Traumatic Brain Injury |
| RE | Right Eye |
| RPQ | Rivermead Post concussion symptoms Questionnaire |
| TBI | Traumatic Brain Injury |
| VAMT | Variable Angle Mirror Test |
| WHO | World Health Organization |
| WPM | Words Per Minute |

# 1 INTRODUCTION

The introductory chapter of this thesis starts with a brief background for the project. Next, some of the basic concepts related to binocular vision, reading and their interaction are described. Thereafter, the concept of eye dominance and its implications are outlined. The chapter concludes with a section on mild traumatic brain injury and its effects on visual function.

## 1.1 BACKGROUND FOR THIS PROJECT

– Consider for a moment the diversity of viewing conditions in which day to day reading is done. The lighting conditions and visibility of text may differ substantially and sometimes be less than optimal. This puts considerable demands on the visual system to allow efficient acquisition of visual information in the reading process. Perhaps not surprisingly, reading-related issues are some of the most common complaints when visual function is affected. The reading-related issues may at times be attributable to visual and binocular function anomalies, e.g. blurred or double vision. However the symptoms are frequently less specific and may be difficult to differentiate from fatigue, memory and concentration issues. This may be even more difficult when visual function anomalies are part of multiple problems following acquired brain injury.

Visual and binocular function may be considered to have a subordinate role in the reading process due to the strong influences by higher order processes. However, considering the fine interaction between binocular coordination, reading eye movements and information processing, any binocular function issues affecting the efficiency are likely to interfere with the process. For patients in the rehabilitation stage following brain injury the additional load of this interference may further burden an already strained capacity.

To address the issues experienced by the patient, an evaluation of reading performance as part of the clinical assessment, may serve to help identifying issues in need for intervention and also to evaluate the outcome. An increased knowledge about functional effects of treatment, and the potential of optimizing visual and binocular function, may be of support in the planning of individualized interventions for patients with visual function anomalies.

This project first takes an experimental approach to estimate the contribution of binocular vision to reading. In the first two papers monocular and binocular reading performance is compared at good and degraded visual conditions. Eye dominance is a factor that may be expected to influence monocular performance and binocular advantage. The third paper explores the occurrence of eye dominance under natural binocular viewing conditions. The project concludes with a multiple case study where symptoms, visual function and reading performance are assessed before and after spectacle treatment in patients with persisting symptoms following mild traumatic brain injury.

## 1.2 BINOCULAR VISION

### 1.2.1 Sensory and motor fusion

Binocular vision is the simultaneous use of both eyes in a way that allows the image formed on each retina to be merged, or fused, into one unified percept. A prerequisite for binocular vision is that the integrity of the ocular media and the refractive power of the eye, allows retinal images of sufficiently similar clarity, size and brightness to be formed on the retinas. Sensory fusion is the mechanism for the unification of the retinal images into binocular single vision. To achieve sensory fusion the retinal images of the object of interest need to be formed on corresponding retinal areas. Retinal correspondence is based on an intrinsic neural mapping of the retina where each local area corresponds to a visual direction relative to the eye, the oculocentric visual direction. The fovea is the central point that gives rise to the principal visual direction. All other points provide secondary visual directions relative the fovea. Each point in the retina has a counterpart in the fellow retina that corresponds to an identical visual direction. When the retinal images are formed on corresponding points they share a common visual direction which enables sensory fusion and binocular single vision.

Motor fusion is the basis for maintaining sensory fusion through the appropriate alignment of the eyes. The correct alignment is acquired through vergence eye movements i.e. the eyes move in opposite directions. This allows for bifoveal fixation of objects at different depth. Once vergence eye movements have aligned the eyes to bifoveal fixation there is no stimulus for further adjustment. However, a small residual alignment error, termed fixation disparity (Ogle, Mussey, & Prangen, 1949), typically remains and is considered to be stimulus for maintaining the vergence response.

### 1.2.2 The Horopter and Panum’s fusional area

The distribution of corresponding retinal points, projected in space at a given fixation distance, can be described using the horopter. The theoretical horopter (the Vieth-Müller circle) is based on the assumption of a geometrical distribution of corresponding points. The locations of the points are then described with a circle passing through the fixation point and the nodal points of the eyes. Another model, the empirical horopter (the Hering-Hillebrand horopter deviation), is based on actual experimental determination of the location of corresponding points. The shape of the empirical horopter is flatter which is believed to be due to differences in distribution of the receptive fields in the nasal and temporal retinas. Objects located on the horopter will be seen in binocular single vision since there will be no disparity. The objects do however not have to be located exactly on the horopter for sensory fusion to occur. There is a narrow allowance proximal and beyond the horopter in which objects can still be fused. This is called Panum’s fusional area (Panum, 1858). Panum’s area is narrowest at the fovea, between 5-20 minutes of arc depending on the measurement technique, and the distribution and symmetry relative to the horopter may differ with the presence of fixation disparity and asymmetric convergence (Steinman, Steinman, & Garzia, 2000). With increasing eccentricity, Panum's area gets wider. This is believed to be due to the increasing size of the receptive fields.

### 1.2.3 Stereopsis

Stereopsis is by definition the relative ordering of visual objects in depth. It occurs when disparate retinal points, within Panum's fusional area, are stimulated simultaneously. For example, when viewing a solid object the slightly different monocular views of the object, due to the lateral separation of the eyes, will cause disparate retinal points to be stimulated. Provided that the fusional area of Panum is not exceeded, sensory fusion can occur. The differences in the retinal images (i.e. disparity) provide cues for the computation of the object's shape which gives rise to a sense of depth, stereopsis.

### 1.2.4 Physiological diplopia

Images formed on retinal points that are disparate enough to fall outside the limits of Panum's fusional area will not be fused and thus not seen single. Instead, the object of regard is perceived double. This phenomenon is a natural consequence of the lateral separation of the eyes and is thus termed physiological diplopia. If an object is located closer than the fixation point in space, the retinal images will be formed temporally of the foveas. This is termed crossed diplopia. On the other hand, if the objected is located beyond the point of fixation, the retinal images will be formed on the nasal retinas relative fovea, and give rise to uncrossed diplopia.

### 1.2.5 Binocular visual direction

As noted in the introduction, oculocentric visual direction provides directional information for a stimulus from an eye-centric perspective. The fovea, projecting to the point of fixation, is the central reference point that gives rise to the principal visual direction. All points outside the fovea provide secondary visual directions. As the eye moves relative the head to make a change of fixation, so does the principal and secondary visual directions. Due to the lateral separation of the eyes a fixated object is seen from slightly different angles. When the eyes fixate an object at far, the visual axes are more or less parallel and the oculocentric principal visual directions towards the object are fairly similar. However, when the fixation is nearer, the eyes must rotate inwards, i.e. converge in order to place the retinal image of the object of interest on the fovea. This means that the visual axes are pointing in opposite directions. Regardless of the difference in monocular view, and despite opposing oculocentric visual directions during convergence, a fixated object is seen singly and in one direction. The reason being that at binocular viewing conditions, the principal visual direction of each eye is unified to a common, subjective, binocular principal visual direction. The computation of a common binocular principal visual direction occurs in accordance with the law of identical visual directions and is thus determined based on retinal correspondence and eye position. The common binocular principal direction is the result of an averaging, or compromise, of the principal oculocentric visual directions and eye position. The reference point for judging the primary, as well as secondary, visual directions now becomes head centric. The reference point tends to be located centrally between the eyes but may be slightly closer to one of the eyes in some subjects (Barbeito, 1981; Porac & Coren, 1986; Sheedy & Fry, 1979). Since this can be likened with seeing the visual scene from an imaginary third eye, located centrally between the eyes, it is frequently referred to as the cyclopean eye. Despite the unification, some monocular information is still available to the visual system. However, research on the ability to determine eye-of-origin for visual information, utrocular discrimination, indicate that this information is not available to consciousness (Barbeito et al., 1985; Ono & Barbeito, 1985). The availability of monocular cues to the visual system may be considered a necessity for binocular vision, for example as stimulus to motor fusion. A further consequence of the monocular cues is that the balancing of the fused percept may be affected by between-eye differences in stimulus properties. Studies of binocular visual direction indicate that relative differences in visibility, i.e. due to blur (Charnwood, 1949), luminance (Charnwood, 1949; Francis & Harwood, 1951; Sridhar & Bedell, 2011) and contrast (Ding & Sperling, 2006; Mansfield & Legge, 1996; Sridhar & Bedell, 2011), as well as weighting of eye position (Sridhar & Bedell, 2011) and interactions between visibility and eye position (Sridhar & Bedell, 2012) affect the balancing. Furthermore, forms of eye dominance have been suggested to affect the balancing (Barbeito, 1981; Sheedy & Fry, 1979).

The description of how a unified single percept of visual direction is achieved is based on the conventional view of the law of identical visual direction leading to fusion. There are however indications of exceptions to this rule suggesting that a single visual direction is achieved through a combination of fusion and suppression. For a review see Ono (Ono, 1991).

### 1.2.6 Binocular summation

Binocular summation refers to the superior performance when performing a task with both eyes as compared to with only one eye. The phenomenon can be attributed to different theories of summation, i.e. probability- and neural summation. The probability summation theory considers the eyes as two independent units, or detectors, and does not necessitate binocular fusion. According to this theory, the summation effect origins from the fact that two detectors have a greater likelihood of detecting a stimulus than only one. The factor for probability summation is typically 1.4, or 40% (Campbell & Green, 1965). The second theory of summation, neural summation, sets out from the basis of binocular fusion, i.e. simultaneous combination of visual information from each eye. The neural summation occurs through a neurophysiological enhancement of the neural signal. An important anatomical location for this process is the striate cortex. Here the monocular neurons synapse with binocular neurons (Hubel & Wiesel, 1959). When corresponding retinal points are stimulated by matching stimulus properties, the binocular neuron simultaneously receives neural signals via monocular neurons of the left and right eye. This leads to a stronger response in the binocular neuron as compared to if it receives signals from only one eye (Hubel & Wiesel, 1962).

The improvement in performance with binocular summation has been shown in both detection and discrimination tasks. The performance is generally better with two eyes but the advantage tends to be smaller and more variable in discrimination tasks (Steinman et al., 2000). The size of the binocular summation effect tend to be the greatest at detection tasks of simple stimuli and reduced with more complex stimuli (Blake, Sloane, & Fox, 1981; Frisén & Lindblom, 1988). Furthermore, the summation effect tends to be greater at reduced stimulus contrast (Banton & Levi, 1991; Bearse & Freeman, 1994; Jones & Lee, 1981; Pardhan, 2003) and with increased retinal eccentricity (Pardhan, 2003; Zlatkova, Anderson, & Ennis, 2001). Studies of the visual processing speed indicate a higher processing speed when using two eyes (Woodman et al., 1990).

### 1.2.7 The visual near response

In order to obtain clear single vision at near work, an appropriate adjustment of eye alignment and eye focus is required. The eyes are rotated inwards, converged. This allows the visual axis of the eyes to cross in a fixation point at a matching depth with the object of interest. Simultaneously, the eyes' focusing mechanism, accommodation, adjusts the eyes' refractive power to allow clear images of the near object to be focused on the retinas. The increase in refractive power occurs through an alteration of the curvature of the crystalline lens in each eye.

The convergence response is induced by retinal disparity while the accommodative response is induced by out of focus retinal images. In both features there is a fast initiating component and a slow sustaining component. Any dysfunction affecting the fast component may result in difficulties to make rapid and precise responses to changes of fixation in depth. If the slow component is affected difficulties to maintain clear single vision over time may arise. Due to the cross-coupling between convergence and accommodation a dysfunction in one of them will affect the other.

## 1.3 READING AND VISUAL FUNCTION

### 1.3.1 Reading performance as clinical measure

Reading performance can be affected by visual and binocular dysfunctions (J. D. Grisham & Simons, 1986; Grosvenor, 1977; Simons & Gassler, 1988; Simons & Grisham, 1987). However, the relationship between visual function issues and reading performance is not fully clear. One complicating aspect is the subject's reading experience. Subjects with different level of reading experience may not be equally susceptible to degraded visual quality due to different dependency on visual detail in the decoding process (Flax, 1970). For example, a proficient reader can more readily make use of cues such as context and meaning, and is thereby not as dependent on full detailed analysis of the words to determine its meaning. Another factor is the reading goal. If the emphasis of reading is comprehension, and particularly if a high level of attention must be sustained over longer periods of time, then any visual or binocular issues are more likely to interfere (Flax, 1970; Simons, 1993).

Another aspect is the adaptability of the visual system. A binocular alignment issue causing double vision may be adapted to through complete suppression of one eye, whereby single vision and reading can be maintained (Flax, 1970). In other cases the visual or binocular issue may be compensated for by exerting extra effort, e.g. fusional reserve- or excessive accommodative effort, but at the cost of visual discomfort. As the discomfort develops with continuous reading it may affect the performance (D. J. Grisham, Sheppard, & Tran, 1993). Examples of the adaptability of the visual system has been demonstrated in experimental research where induced moderate refractive error (Wolffsohn, Bhogal, & Shah, 2011), or induced extra vergence demand (Dysli, Vogel, & Abegg, 2014), did not cause a significant reduction of reading performance, although it may be at the cost of significantly increased visual symptoms (Rosenfield et al., 2012).

Due to the complexity of determining if visual function issues interfere with reading ability, the use of standard clinical measures of visual function only, may not be sufficient. To address these issues, measuring reading performance may serve as a complement to clinical assessment of visual function. Studies of reading performance in populations with ophthalmologic issues indicate that clinical reading tests, despite their in some cases artificial nature, are strongly predictive of normal day to day reading performance (Rubin, 2013). Furthermore, differences between measured reading performance and self-reported reading ability can help to earlier identify patients in a pre-clinical stage of visual disability (Guralnik et al., 1989). A further argument for considering reading performance as a clinical measure is that the reading performance has been found to be one of the strongest predictors of vision-related quality of life (Hazel et al., 2000).

There are several different types of clinical reading tests (Rubin, 2013). These include lists of unrelated words of decreasing font size (e.g. Bailey-Lovie word reading card), standardized sentences (e.g. MNREAD reading chart) and paragraphs of text (e.g. IReST). The choice of test depends on the purpose of the evaluation. For the purpose of estimating how well a patients reads ordinary text it is suggested to use longer passages of text (Rubin, 2013). Using paragraphs of text tend to produce results with less variability compared to using single sentences which serves to make the test more sensitive to changes over time (Altpeter et al., 2015).

There is currently no consensus on how to quantify reading performance. A common measure is the product of reading speed and comprehension (Castelhano & Muter, 2001; Jackson & McClelland, 1979; Rahman & Muter, 1999). It is a composite measure of reading performance that balances for assumed trade-offs between reading speed and comprehension (Wickens, 1992). However, comprehension is estimated based on the percentage of correctly answered questions after reading and thus strongly dependent on the type of questions asked. This makes comprehension scores less reliable and therefore more difficult to compare between studies. It is therefore suggested to report reading speed and comprehension separately as well (Öquist, 2006).

Some of the measures that have been developed for low-vision assessment are reading acuity, the smallest print that can be read, maximum reading rate, the fastest reading rate regardless of print size, and critical print size, the smallest print size at which maximum reading rate can be maintained (Mansfield, Legge, & Bane, 1996; Rubin, 2013). For the purpose of evaluating reading performance in patients with binocular function issues the reading rate of continuous text appears as an appropriate measure of clinical and practical relevance that indicates at what pace the reader can process the information.

### 1.3.2 Reading eye movements

Reading eye movements consists of a sequence of saccades interrupted by brief fixations. The saccades are required because of acuity limitations in the retina. The stepwise eye movements successively bring the words into foveal vision for detailed analysis. The length of the saccades is typically 1.5-2.0 degrees (6-8 characters) and a fixation lasts for on average 250 ms but may range between 100-500 ms (Rayner, 1998). The majority of saccades are directed forward in text however about 10-15% of saccades are directed backward, regressive saccades. The regressive saccades can range from a few character spaces, e.g. if the previous saccade was too long, or it can be several words long in the event of comprehension difficulty.

The foveal region, where characters can be identified, subtend approximately two degrees (4-6 characters). The parafoveal region extends to about five degrees on either side of fixation and offers considerably lower acuity. Still, the acuity is sufficient to allow information about word length, up to eight characters to the right of fixation, and further to the periphery, information about word shape (Rayner, 1998). During the fixation, information is not only acquired from the point of fixation but from an asymmetric region around the fixation point, the perceptual span. The symmetry and size of the perceptual span varies with different writing systems. For English it typically extends from up to 3-4 characters to the left of fixation and up to 14-15 characters to the right but it varies continuously with the difficulty of the text (Rayner, 1998). For fluent reading the reader thus attends to visual information that extends beyond the span where letters and words can be recognized. A majority of the words are fixated while short words, which can be anticipated or recognized without foveation, are skipped. The likelihood of a word being fixated depends on factors such as word length, word frequency, context and if it is a content word. Longer words, low frequency and content words are more likely to be fixated. Furthermore, if the word before was skipped the likelihood of next upcoming word to be fixated increases. Words can be fixated only once or be subject to multiple fixations. The position of the first fixation has been shown to influence the likelihood of a re-fixation. The further from the preferred (Rayner, 1979) or optimal (O'Regan & Levy-Schoen, 1987) viewing location of the word, the more likely a re-fixation occurs. This has been termed the re-fixation effect. The optimal viewing position is where the recognition time of the word is minimized and thus provides the most efficient processing of the word. When reading isolated words the optimal viewing position is at the center of the word while at continuous reading it tends to be located between the beginning and center of the word (Rayner, 1998).

### 1.3.3 Binocular coordination in reading

During conjugate saccades there tend to be an asymmetry in amplitude, peak velocity and duration between the abducting and adducting eye (Collewijn, Erkelens, & Steinman, 1988). As a result there is frequently a disparity between the eyes at the landing point of the saccade. This saccadic asymmetry occurs also in reading where the magnitude of the asymmetry is about 5% of the saccadic amplitude at long saccades (10-12 characters) and 15% at short saccades (2-3 characters) (Heller & Radach, 1999). The disparity is adjusted for through a vergence movement, the post saccadic drift, which largely reduces the disparity during the first 50-100 ms of fixation (Jainta et al., 2010; Vernet & Kapoula, 2009). In about 50% of the reading fixations, a disparity corresponding to a character width or more remains after the post-saccadic drift (Blythe et al., 2006; Juhasz et al., 2006; Liversedge et al., 2006). The disparity may be either crossed, where the visual axis intersect proximally of the media, or uncrossed, where the intersection is beyond the media. Even though the disparity may exceed the expected limits of Panum's fusional area for approximately half of the fixations, the reader does not experience diplopia. This may raise the question if reading is done under binocularly fused conditions. There are however indications that fusion may be retained at disparities up to 3° depending on measurement method (von Noorden & Campos, 2002). Furthermore, experimental research, on the computation of saccade metrics during reading, indicates that the computation is indeed based on a unified percept of the disparate oculocentric signals (Liversedge et al., 2006). Direct comparisons of monocular and binocular reading eye movements indicate clear differences in post-saccadic vergence eye movements suggesting an active fusional process during binocular reading (Jainta & Jaschinski, 2012). Furthermore, recent research on the effects of monocular versus binocular reading indicates binocular advantages in the lexical processing (Jainta, Blythe, & Liversedge, 2014).

### 1.3.4 Binocular advantages attributable to reading performance

Efficient reading eye movements play an import role for reading performance. The fixations account for almost 90% of the reading time. The durations and number of fixations thus play a major role for reading speed. An optimal first fixation position, following an accurate saccade, minimizes the recognition time of the word and reduces the likelihood for re-fixations. The parafoveal preview allows for word skipping. This supports the reading efficiency in that reading fixations are prioritized for longer or less frequent words that require direct fixations to be recognized and processed. The abilities to discriminate the letters at the point of fixation, as well as getting a sufficient preview of words ahead of fixation in order to plan the next saccade, are therefore key factors for efficient reading eye movements and an optimal reading speed. Subsequently, studies of the visual function versus reading performance have identified the necessity of a reserve in acuity and contrast, along with sufficient field of view, to achieve and maintain optimal reading speed (Whittaker &

Lovie-Kitchin, 1993). A contrast reserve, i.e. print contrast vs. contrast threshold, of at least 20:1 is indicated for achieving peak reading velocity, while at 3:1 and lower, the reading speed abruptly drops off (Legge, Rubin, & Luebker, 1987; Whittaker & Lovie-Kitchin, 1993). The acuity reserve, i.e. print size vs. visual acuity, is more variable with a span of 6:1-18:1, however with a critical limit at 3:1, where reading speed rapidly declines (Legge et al., 1985; Whittaker & Lovie-Kitchin, 1993). Regarding the field of view, it is indicated that peak reading speed is reached when it extends to about 15 characters on either side of the point of fixation, with a more rapid decline in reading speed when the field of view shrinks below about eight characters (Rayner et al., 1981).

From a visual function point of view these factors are all subject to different degrees of a binocular summation. The binocular summation effect of visual acuity at suprathreshold may be improved by around 10% at high contrast, however with great variability, (Bárány, 1946; Frisen & Lindblom, 1988; Heravian, Jenkins, & Douthwaite, 1990) and may exceed 40% at contrast threshold (Banton & Levi, 1991; Campbell & Green, 1965). Regarding the field of view studies indicate that the summation effect increases with increasing retinal eccentricity (Zlatkova et al., 2001), particularly at lower contrasts (Pardhan, 2003). The peripheral resolution acuity improved by around 16% as compared to around 5% at the fovea (Pardhan, 2003; Zlatkova et al., 2001). Another factor is the visual processing speed. There are indications that binocular vision leads to shorter reaction time, faster recognition and encoding of single words (Woodman et al., 1990).

### 1.3.5 Visual and binocular dysfunction interference with reading

Day to day reading occurs at a multitude of different reading distances however continuous reading tend to be done at near distance. Near work such as reading means higher demands on the binocular functions to maintain clear single vision over time. In the presence of normal binocular function there is capacity to manage the added load. However, any binocular anomalies are likely to cause symptoms (Yekta, Jenkins, & Pickwell, 1987; Yekta, Pickwell, & Jenkins, 1989). Despite some conflicting results, previous studies indicate that visual function anomalies, e.g. hyperopic and astigmatic refractive error, anisometropia, heterophoria, low fusional vergences and convergence insufficiency may affect reading performance (J. D. Grisham & Simons, 1986; Grosvenor, 1977; Simons & Gassler, 1988; Simons & Grisham, 1987). Studies on effects of accommodative anomalies are scarce. There are however indications of differences in baseline tonic accommodation, and the rate of adaptation between symptomatic and asymptomatic subjects following continuous reading which, along with tonic vergence, may be associated with symptoms at near (Fisher et al., 1987).

The interference of visual function anomalies on the reading process may be categorized as *functional efficiency interference* and *perceptual interference* (Simons, 1993). With functional efficiency interference reading is still feasible but at the cost of reading efficiency and visual discomfort. The increased effort of compensating for visual function anomalies, and maintaining binocular single vision, may lead to less efficient reading eye movements, e.g. more fixations and re-readings, and slowed reading speed. Perceptual interference relates to disturbance of the higher order processing of the text content. The systematic reading pattern is then disrupted due to for example double vision, extensive blur, or fixation or saccadic issues. The reading process may then be difficult to maintain or even break down, whereby the ability to read and understand what is read, is limited or even impossible. There are most likely intermediate stages of these categories, e.g. in patients who are subject to cognitive fatigue, as in patients with MTBI.

## 1.4 EYE DOMINANCE

Eye dominance can be broadly described as the preference for one eye's view. Forms of eye dominance may be apparent both in one-eyed tasks and in the process of combining the two views under binocular visual conditions. There are different criteria and methods for determining dominance and its relation to, and significance for, visual and ocular motor function is not fully understood (B. J. Evans, 2007; Mapp, Ono, & Barbeito, 2003). Based on a comprehensive review of methods to determine eye dominance (B. J. Evans, 2007) it was suggested that eye dominance may be classified into sighting-, motor-, or sensory dominance.

Sighting dominance tests involve the alignment of a near and far target arranged in manner that only allows the use of one eye's view. For example, when sighting or using an instrument with only one eye-piece, most people tends to consistently choose the same eye. This behavior can be predicted, with a fair level of certainty, by using sighting dominance tests. In order to avoid double vision or visual confusion during these tasks, the view of the fellow eye, not used for alignment, needs to be disregarded, or suppressed. The dominant eye identified with these tests may be considered the eye least likely to be suppressed (B. J. Evans, 2007). Some of the common tests are the hole-in-the-card (Durand & Gould, 1910), Miles ABC (Miles, 1929), or Porta test (Porta, 1593). These tests tend to deliver consistent test responses (Ehrenstein, Arnold-Schulz-Gahmen, & Jaschinski, 2005; Li et al., 2010; Rice et al., 2008; Zeri et al., 2011) and offer a limited possibility for a graded assessment. Sighting tests that allow binocular visual feedback do however indicate that sighting dominance may not be strictly aligned with one eye; instead, sighting can appear to occur from a reference point along a continuum between the eyes (Charnwood, 1949; Francis & Harwood, 1951).

Motor dominance refers to an asymmetry in motor function (Walls, 1951), i.e. the preference for an eye that can be observed in eye movements. It may be determined with measures of fixation disparity (Mallet, 1966; Ogle, 1962) where relative differences in displacement of the eyes' fixation are assessed. The eye with the smallest displacement is considered the dominant eye. Other tests involves binocular fixation under increasing prismatic vergence load (Stein & Fowler, 1982) or near-point-to-break testing where the eye that maintains fixation when fusion breaks is considered the dominant eye (Mills, 1928). Forms of motor dominance have been observed in experimental research on achieving and maintaining fixation following versional (Oishi et al., 2005) and vergence eye movements (B. J. Evans, 2007; Han, Seideman, & Lennerstrand, 1995; Kawata & Ohtsuka, 2001; van Leeuwen et al., 1999).

Sensory dominance refers to an asymmetry in the interaction between the eyes' sensory visual input under binocular viewing conditions. In the clinical setting sensory dominance can be estimated using for example blur suppression (Humphiss, 1969; Schor, Landsman, & Erickson, 1987). In experimental settings the methods typically apply dichoptic presentation, i.e. separate presentation of stimuli to each eye. Sensory dominance is determined by estimating the interocular difference in; duration of exclusive visibility at binocular rivalry (Handa et al., 2004; Handa et al., 2012), the threshold for detection (Li et al., 2010; Yang, Blake, & McDonald, 2010), or target detection rate (Valle-Inclán et al., 2008). Sensory dominance tests offer a way of grading the dominance by comparing relative difference in sensitivity between the eyes.

Attempts to relate eye dominance tests from the different categories tend to provide inconsistent results (Coren & Kaplan, 1973; B. J. Evans, 2007; Li et al., 2010; Ooi & He, 2001; Rice et al., 2008). This is likely to be due to the differences in what mechanisms are involved in different tests. There are however indications that the strength of dominance is a factor for the inter test agreement (Handa et al., 2004; Li et al., 2010) as well as the significance of eye dominance for visual and binocular function (Handa et al., 2005).

## 1.5 MILD TRAUMATIC BRAIN INJURY

Traumatic brain injury (TBI) is one of the major causes of disability adding considerable pressure on the healthcare systems and society (Grabow, Offord, & Rieder, 1984; Hartvigsen et al., 2014; Kraus et al., 2005). It is estimated to affect 10 million annually and is considered a global health issue according to the World Health Organization, WHO. The incidence of TBI in Europe is estimated to 235/100 000 annually (Tagliaferri et al., 2006). TBI is categorized as mild, moderate or severe based on clinical parameters in the acute stage (Teasdale & Jennett, 1974). Mild traumatic brain injury (MTBI), mainly concussions, represents approximately 70-90% of all hospital-treated TBI (Cassidy et al., 2004).

Mild traumatic brain injury is defined as an acute brain injury, resulting from mechanical energy to the head from external physical forces, inducing physiological disruption of brain function manifested by at least one of the following; (1) any period of loss of consciousness, (2) any loss of memory for events immediately before or after the accident, (3) any alteration in mental state at the time of the accident (e.g., feeling dazed, disoriented, or confused), and (4) focal neurological deficits that may or may not be transient; but where the severity of the injury does not exceed the following: loss of consciousness for approximately thirty minutes or less, after 30 minutes an initial Glasgow Coma Scale (GCS) of 13-15, post traumatic amnesia not greater than 24 hours. The definition is based on the recommendations by the American Congress of Rehabilitation Medicine (Mild Traumatic Brain Injury Committee, 1993).

Transient dysfunctions are common following MTBI but the prognosis is in most patients good (Carroll et al., 2014; Cassidy et al., 2014) and the patients can return to normal activities within a few weeks without further intervention. However, a minority of the patients may experience long-lasting physical, cognitive and emotional symptoms that affect wellbeing, social- and working life. The symptoms are referred to as post-concussive symptoms, and may include headache, dizziness, difficulty concentrating, memory issues, fatigue, irritability, anxiety, sensitivity to noise or light, and visual disturbances (Bohnen, Twijnstra, & Jolles, 1992; R. W. Evans, 1992). This has been found to imply direct and indirect costs in the form of care seeking and cost for sickness absence (Hartvigsen et al., 2014; Kraus et al., 2005). There are different diagnostic criteria symptom lists used to assess post-concussive symptoms, e.g. the fourth edition of the Diagnostic and Statistical Manual of Mental Disorders (DSM-IV)(APA, 1994), the 10th International Classification of Diseases ICD-10 (WHO, 1992), and the Rivermead Post Concussion Symptoms Questionnaire (RPQ) (King et al., 1995). Around 15% of patients with MTBI have been estimated to experience persisting symptoms (Alexander, 1995; Ruff, 2005). However, there is uncertainty in the estimates due differences in the diagnostic criteria (Boake et al., 2005; Laborey et al., 2014). Furthermore, the diagnosis to a large extent is based on subjective symptoms and it has been indicated that these may be related to secondary factors (Carroll et al., 2004; Greiffenstein, 2009). Another complicating factor is that the symptoms are not specific to MTBI but may be found in trauma patients without head injury (Meares et al., 2011; Ponsford et al., 2012) and in healthy populations (Chan, 2001; Dean, O'Neill, & Sterr, 2012; Wong, Regennitter, & Barrios, 1994). Due to the difficulty of defining these long-lasting problems they are referred to as persisting symptoms after MTBI in this thesis. The causes of these persisting symptoms are despite extensive research, and advanced diagnostic tools, still in many parts unknown. For these patients a well-functioning chain of care and individualized evidence based interventions are needed (Nelson Sheese & Hammeke, 2014; Nygren-de Boussard et al., 2014).

Visual dysfunctions and symptoms may be part of the issues that complicate the patient’s ability to return to normal activities. The Rivermead Post Concussion Symptoms Questionnaire have specific items regarding visual function where the patient is asked to indicate the severity of visual symptoms, i.e. blurred vision and double vision. Follow-up studies of MTBI-patients three months post injury have found a prevalence of blurred vision of 6.0-16.2% and double vision 2.0-6.2% (Kraus et al., 2009; Laborey et al., 2014; Lannsjo et al., 2009). Studies involving patients with vision based symptoms in the sub-acute stage following MTBI, have found an occurrence of accommodative- (24.2-62.0%), vergence- (23.3-56.3%), and ocular motor related dysfunctions (6.0-51.3%) (Alvarez et al., 2012; Brahm et al., 2009; Ciuffreda et al., 2007; Goodrich et al., 2013; Stelmack et al., 2009). Case-control studies, involving patients in the sub-acute stage following MTBI and controls with no history of MTBI, have also found significantly higher prevalence of binocular and ocular motor dysfunctions in similar ranges (Capo-Aponte et al., 2012). A study of long-term visual dysfunctions (years) following MTBI found accommodative dysfunctions in 23.0% of the patients and vergence issues in 25.0% (Magone, Kwon, & Shin, 2014). Long-term case-control studies of static and dynamic properties of accommodative (Green et al., 2010) and vergence functions (Szymanowicz et al., 2012) found dysfunctions to be significantly more prevalent in MTBI-patients compared to controls. These findings indicate a higher occurrence than expected in a general population (Porcar & Martinez-Palomera, 1997; Rouse et al., 1999) or among patients seeking care at an eye clinic due to vision based symptoms (Hokoda, 1985; Lara et al., 2001) where prevalence of accommodative issues may range between 9.4-16.8% and vergence related issues between 4.2-13.0%.

Self-reported and observed reading-related issues have been reported both in the sub-acute stage and up to a year post injury in patients with blast and non-blast induced MTBI (Brahm et al., 2009; Capo-Aponte et al., 2012; Magone et al., 2014). Given the complexity of the reading process and as suggested by symptoms related to mental fatigue and visual information processing (B. Johansson, Berglund, & Ronnback, 2009; Raymond et al., 1996) reading-related issues are likely to be a combination of visual and cognitive dysfunctions. The additional load of coping with visual function deficits may however further burden an already strained cognitive capacity.

# 2 AIMS OF THE PROJECT

The main aim of the project was to estimate the contribution of binocularity in reading in healthy subjects and in patients with MTBI. A second aim was to evaluate the role of eye dominance in in reading and the occurrence of graded eye dominance under true binocular viewing conditions. The third and final aim was to evaluate the effect of spectacle treatment on visual function, symptoms and reading performance in patients with MTBI.

## 2.1 PAPER I

The main aim of the first study was to study the differences in reading performance between monocular and binocular reading in the typical reader. The secondary aim was to assess any asymmetry in monocular performance, i.e. if one of the eyes was superior in performance, and how this might be associated with the sighting dominant eye.

## 2.2 PAPER II

The main aim of the second study was to compare monocular and binocular reading performance at three levels of reduced stimulus contrast and to assess the level of binocular superiority as a measure of binocular contribution. A secondary aim was to assess any asymmetry in monocular performance and its possible correspondence to sighting dominance and also to compare dominant and non-dominant eye to binocular performance.

## 2.3 PAPER III

The purpose of the third study was to evaluate if different degrees of eye dominance can be identified under binocular viewing conditions using two principles; (1) how the subject positions during binocular sighting and (2) how the binocular percept of a scene is affected by the subject's individual weighting of monocular views. The first aim was to assess the subjects' baseline response, i.e. without any manipulation of visibility in either eye. The second aim was to complement the baseline result, by assessing if there was an interocular difference in tolerance to degraded visibility. The third aim was to assess how eye dominance in these two binocular tasks agreed with a sighting dominance test.

## 2.4 PAPER IV

The main aim of the fourth study was to evaluate the effects of spectacle treatment on visual symptoms and binocular functions in a group of visually symptomatic patients with persisting symptoms after MTBI. The second aim was to evaluate reading performance before and after treatment and to estimate the contribution of binocularity by comparing monocular and binocular reading.

# 3 MATERIALS AND METHODS

## 3.1 PAPER I

A total of 18 subjects were included in the study. The mean age of the subjects was 25.2 ± 4.5 years and 12 subjects (67%) were female. The inclusion criteria for participation were; subjectively asymptomatic when reading, a normal binocular status, not diagnosed with ocular disease or reading difficulties and able to read Swedish text fluently.

All subjects went through a visual examination including a brief history, visual acuity at far and near (Logarithmic Visual Acuity Chart 2000 'ETDRS' 4 m/40 cm), stereoscopic visual acuity (TNO random dot test), cover test, fusional reserves, eye motility, near point of convergence and near point of accommodation (RAF ruler) and a suppression test (Bagolini striated lenses). Symptoms experienced during day-to-day near work were assessed using a translated version of the Revised Convergence Insufficiency Symptom Survey (CISS) (Borsting et al., 2003; Rouse et al., 2004). All subjects had normal binocular status with stereo-vision of 60 seconds of arc or better and were fluent in Swedish. Eye dominance was assessed at far (400 cm) and near (40 to 50 cm). At far, the hole-in-the-card sighting test was used (Durand & Gould, 1910). For near dominance assessment the near hole-in-the-card sighting test was used (Rice et al., 2008).

A Tobii 1750 eye tracker (Tobii Technology, Stockholm, Sweden) was used for eye movement recording. The recorded eye movement data were processed using Visiolyzer, a software developed at our laboratory. Fixations were defined according to a fixation dispersion model, i.e. when the center of gravity of recorded fixation points stayed within a radius of 0.75 degrees (2.7 character spaces) for a minimum of 50 ms. Saccades were defined as the movement between two adjacent fixations. Nine texts from the International Reading Speed Texts (IReST) (Trauzettel-Klosinski, Dietz, & Group, 2012) were used. The IReST texts are validated in 17 languages including Swedish. The Swedish texts have the exact same number of words (146), characters (684) and lines (16) and all texts have the same readability index (LIX 35). The mean word length is 4.61±0.01 characters. The texts were presented as a single paragraph subtending 14.3 by 17.1 degrees on the integrated screen of the eye tracker (Figure 1). The subject was seated unrestrained and centered at 60 cm in front of the display and were instructed to read the texts for comprehension. They were informed that they would need to answer questions about the content after finishing reading.

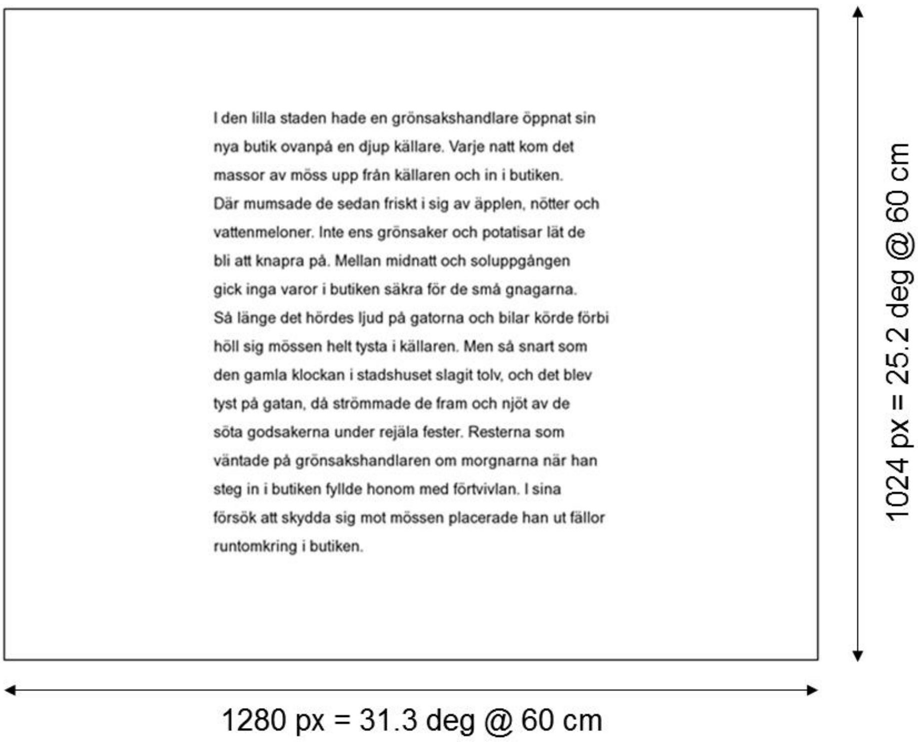


**Figure 1.** Stimuli used in the experiment with screen dimensions and visual angles.

The experiment was designed as a balanced repeated-measurements study, where each subject silently read texts under all conditions (monocular right, monocular left and binocular) while eye movements were recorded. The conditions were repeated three times, so that each repetition began with a different condition and no condition was immediately repeated. Each text was read once by each subject. During monocular reading, one of the eyes was covered by an infra-red transmissible occluder allowing binocular recording, which is required by the Tobii eye tracker.

## 3.2 PAPER II

A total of 18 subjects with a mean age of 24.0 (3.2) years were included in the study. Eight subjects (44%) were female. The inclusion criteria were age 18–40 years, non-symptomatic at reading and near work, normal binocular vision, no diagnosis of reading difficulty or ocular disease, and an ability to read Swedish fluently. Methods for visual examination, symptom assessment and determination of eye dominance were the same as in paper I. All subjects were fluent in Swedish and had normal binocular vision status with stereovision of 60 seconds of arc or better.

Eye movements were recorded with a Tobii T120 eye tracker (Tobii Technology, Stockholm, Sweden, http://www.tobii.com). The eye tracker is display mounted and records eye movements at 120 HZ using infrared video technology. The subject was positioned centered and unrestrained 60 cm in front of the display and instructed to read for comprehension. The recorded eye movement data were processed using Visiolyzer, a software developed at our laboratory. Eye movements were defined according to the same model as in paper I.

The experimental design consisted of balanced repeated measurements where each subject silently read IReST texts (Trauzettel-Klosinski et al., 2012) under all conditions while their eye movements were recorded. There were three levels of viewing conditions (monocular left, monocular right, and binocular) and three levels of stimulus contrast. Each IReST text was rendered to three levels of contrast (Michelson contrast 10%, 20%, and 40%) by keeping the background luminance constant at 210 candela/$m^2$ while the luminance of print was adjusted. The luminance levels were measured with a Hagner S4 lightmeter (Hagner AB, Solna, Sweden, http://www. hagner.se). The lowest contrast level (Michelson 10%) was decided based on screen resolution limitations and pilot testing. The order of the conditions and stimulus contrast were counterbalanced. Each text was read once by each subject. The dependent variables examined were reading speed, fixation duration, progressive saccade length, and proportion of regressive saccades.

## 3.3 PAPER III

A total of 32 healthy subjects (age 23.5±2.8 years, 26 female) were included in the study. The inclusion criteria were; a monocular visual acuity at far of 0.10 logMAR or better (Visual Acuity Chart 2000 “ETDRS” 4 m), not more than one line visual acuity difference between the eyes, a stereo vision acuity of 60 seconds of arc or better (TNO random dot test), no suppression at test distances (Worth four-dot test). All subjects went through an examination to ensure they were meeting the inclusion criteria. The experiments took place in an evenly lit room (mean illumination 550 lux). The total participation time was approximately one hour at one occasion. The order of the experiments was first the Binocular Sighting Test (BST), followed by the Variable Angle Mirror Test (VAMT), and finally the hole-in-the-card sighting test (HICT). The HICT was saved for last to reduce any effects of awareness of sighting dominance during the experiments.

The BST was derived from the experiments by Charnwood (Charnwood, 1949) and Francis & Harwood (Francis & Harwood, 1951). The task was to align a near and far object suspended from the ceiling (Figure 2). The subject was instructed to fixate the more distant bead and to position so that it was seen through the closer positioned ring. A pointer above the head, and not seen by the subject, indicated the subjects’ head position (i.e., projection center). This position was then recorded by taking a photograph of the face and pointer with an aligned digital camera. In the post processing of the photo a scale was inserted using a photo editing software (Inkscape 0.48.2, inkscape.org). The scale ranged from the center of the right pupil (0) to the center of the left pupil (100). The pointer´s position along this scale indicated the projection center.


**Figure 2**. A camera (a), a bead (b) (diam. 15 mm), a ring (c) (diam. 15 mm) and a pointer (d) was aligned on a straight line (i.e., stimulus line). The distance between bead and ring (c-b) was 45 cm and between ring and eye (d-c) 155 cm.

Filter bars with a combination of Bangerter filters and clear tape were used to degrade visibility. The filters were mounted in segments (30x30 mm) on bars of 2 mm glass. The first segment (F0) on the filter bar was plane glass with no occlusion foil attached. The next three segments (F1-F3) were covered with filters with an increasing level of degrading effect. In the binocular sighting test, the different filters were mounted on separate bars, and the test order of filtered eye and filter strength were counterbalanced. The baseline projection center was the calculated mean of projection center when F0 was held in front of left and right eye. The experimental procedure consisted of two conditions, the filter bar held in front of left eye or right eye, and four different filter steps. Each subject did the experimental procedure once.

The VAMT origins from the experiment by Björk (Bjork, 1980). In this test two plane glass mirrors, attached by a black hinge, are arranged at a square angle (Figure 3). The subject is positioned 50 cm centered in front of the hinge and looks straight ahead at his or her face. As can be seen from the ray trace, the subject will be looking at a non-reversed image of the face in the mirror. The hinge midway between the subject and the mirror image will appear as two vertical lines due to physiological crossed diplopia. The theory behind the experiment is that the subjects' percept of the physiological double images, hypothetically influenced by eye dominance, will decide over which eye the image of the hinge will be perceived. The stronger the eye dominance, the more likely the subject will suppress one double image, and the remaining image will appear to be superimposed on the dominant eye. The experimenter then held the filter bar in front of the subjects left or right eye, starting with no filtering (plane glass). For each subsequent increase of filter level, the subject was instructed to look at each eye in turn in the mirror image, and report which eye the image of the hinge appeared to be in front of. The experimental procedure consisted of two conditions, the filter bar held in front of left eye or right eye, and four different filter steps. In summary each subject did eight trials. The averaged response when plane glass was held in front of left and right eye were recorded as the baseline response. The subject's response was evaluated according to a relative score. If the hinge was perceived to cover the right eye it was recorded as score 1, if covering left eye it was scored as -1. In the event the subject perceived two hinges of equal saliency a score of 0 was recorded.

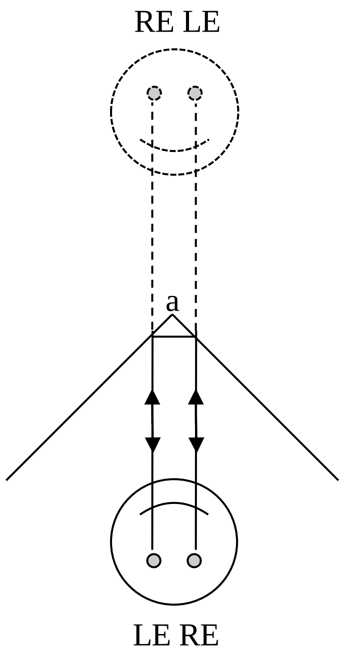


**Figure 3**. The Variable Angle Mirror Test. The subject is looking at a non-reversed image of his or her face and the hinge (a) between the mirrors is perceived in crossed physiological diplopia.

In the hole-in-the-card test the subject held a card (20.0x12.8 cm) with both hands. In the center of the card there was a three cm diameter hole. The subject was instructed to always look with both eyes and then, in one movement, raise the arms in order to visually align the hole in the card with a target at 2 meters distance. The eyes were then covered one at a time and the eye that kept the alignment was recorded as the dominant eye. The procedure was repeated three times.

## 3.4 PAPER IV

Eight patients with a documented history of MTBI, referred to the Department of Rehabilitation Medicine Stockholm due to persisting symptoms after MTBI, were examined for visual dysfunctions. The median age of the patients was 32.5 years (min 21, max 56) and five patients (62.5%) were female. The first optometric examination took place between three and 82 months post injury (mean 19.9±25.1, median 10 months).

Visual symptoms were assessed using the Convergence Insufficiency Symptom Survey (CISS) (Borsting et al., 2003; Rouse et al., 2004). Visual function was assessed by using a standard clinical procedure including; visual acuity at far (Visual Acuity Chart 2000 “ETDRS” 4 m) and near (KM), objective refraction and subjective balancing of the refraction in a trial frame, near point of convergence and monocular and binocular near point of accommodation (RAF-ruler), accommodative facility (spherical flipper, +/- 2 diopters), binocular alignment (covertest) and assessment of heterophoria at 40 cm and 4 m (prism covertest), fusional vergence at 40 cm and 4 m (prism bar), stereo acuity (TNO Random Dot Test) and ocular motility.

Reading performance was assessed by measuring reading speed, fixation duration, number of fixations, length of progressive saccades and proportion of regressive saccades (re-readings). The patients quietly read IReST texts in Swedish (Trauzettel-Klosinski et al., 2012). The subjects were instructed to read at their own normal pace and to read for comprehension. Reading eye movements were recorded using a Tobii T120 eyetracker (Tobii Corp., Stockholm, Sweden, www.tobii.com). Eye movements were defined according to the same model as in paper I and II.

After the first examination the patients were provided with a prescription for spectacles intended to compensate for their optometric deficit at near distance and were instructed to wear the glasses whenever doing near work. The spectacles were dispensed by an optometrist of the subject's choice.

At the second visit, after been using the spectacles for five to 12 months (mean 8.5±2.5 months), the subjects were re-examined for visual functions, symptoms and reading performance. At this occasion both monocular and binocular reading performance was recorded.

# 4 RESULTS

## 4.1 PAPER I

### 4.1.1 Eye dominance assessment

According to the hole-in-the-card sighting test performed at distance, 12 subjects (67%) were right eye dominant and six subjects (33%) were left eye dominant. The near sighting test showed 11 subjects (61%) to be right eye dominant, six subjects (33%) to be left eye dominant and one subjects to have no dominance. Five subjects (28%) had a different dominant eye depending on if tested at far or near.

### 4.1.2 Monocular versus binocular reading performance

Monocular reading speed (dominant and non-dominant averaged) was slower by 2.1% compared to binocular but the difference was not significant. There were small but significant differences in the fixation durations ($p < 0.01$) and the lengths of regressive saccades ($p = 0.01$) between the conditions. Reading monocularly increased the fixation duration by 16.6 ms and the regressive saccades became 0.12 degrees (0.4 characters) longer. None of the other eye movement measures differed significantly (Table 1). There was no difference in comprehension between the conditions.

**Table 1.** Binocular and monocular reading performance

| | Binocular reading | Monocular reading |
|---|---|---|
| Reading speed (WPM) | 269.6±33.5 | 264.2±36.3 |
| Comprehension (%) | 94.9±7.4 | 92.8±6.2 |
| Fixations per word | 0.96±0.11 | 0.94±0.13 |
| Fixation duration (ms) | 187.4±23.5 | 204.0±29.2 |
| Progressive saccade length (char.) | 7.4±0.9 | 7.4±1.0 |
| Regressive saccade length (char.) | 4.8±1.4 | 5.2±1.6 |
| Proportion of regressive saccades | 0.2±0.1 | 0.2±0.1 |

### 4.1.3 Binocular versus dominant and non-dominant eye performance

With dominance determined at distance, there was a significant difference in reading speed between reading with the non-dominant eye and reading binocularly ($p = 0.03$) (Figure 4). There were also significant differences in fixation durations for the dominant ($p < 0.01$) and the non-dominant ($p < 0.01$) eyes compared with reading binocularly. With dominance determined at near, there were significant differences between reading binocularly and with the dominant ($p < 0.01$) and non-dominant ($p < 0.01$) eyes for fixation durations; for the non-dominant eye there was also a significant difference in regressive saccade length ($p < 0.01$).

### 4.1.4 Dominant versus non-dominant eye

The comparison of reading performance for dominant and non-dominant eye, as determined at far, showed no significant differences. However, reading with the non-dominant eye, as determined with the near test, showed an increased mean progressive saccade length by 0.06 degrees (0.2 characters) ($p = 0.03$). The agreement between the dominant eye and faster reading speed was 56% with dominance determined at distance and 44% with dominance determined at near.

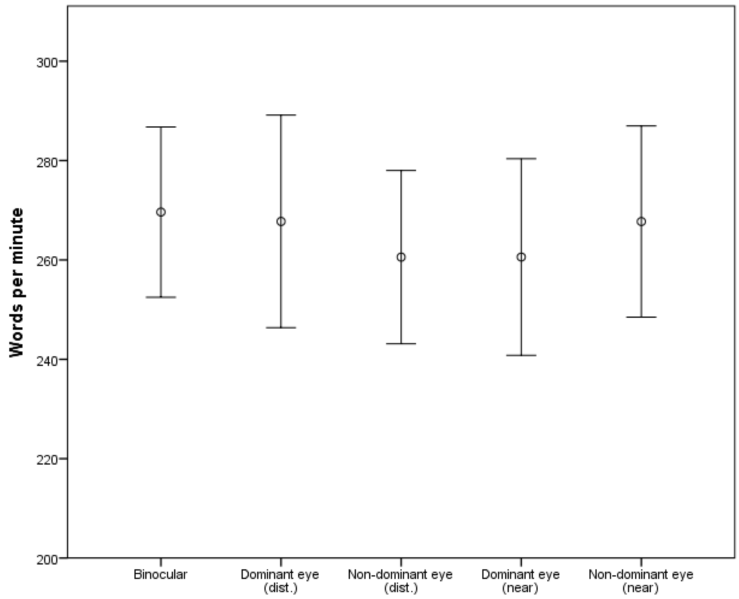


**Figure 4**. Reading speed for binocular, dominant and non-dominant eye (as determined by distance and near testing). Error bars represent 95 % confidence interval.

## 4.2 PAPER II

### 4.2.1 Monocular versus binocular reading performance

Monocular reading speed (left and right eye averaged) was slower than binocular by 6.9% at 40% contrast, by 9.3% at 20% contrast, and by 21.1% at 10% contrast. There was no significant interaction effect (Figure 5).

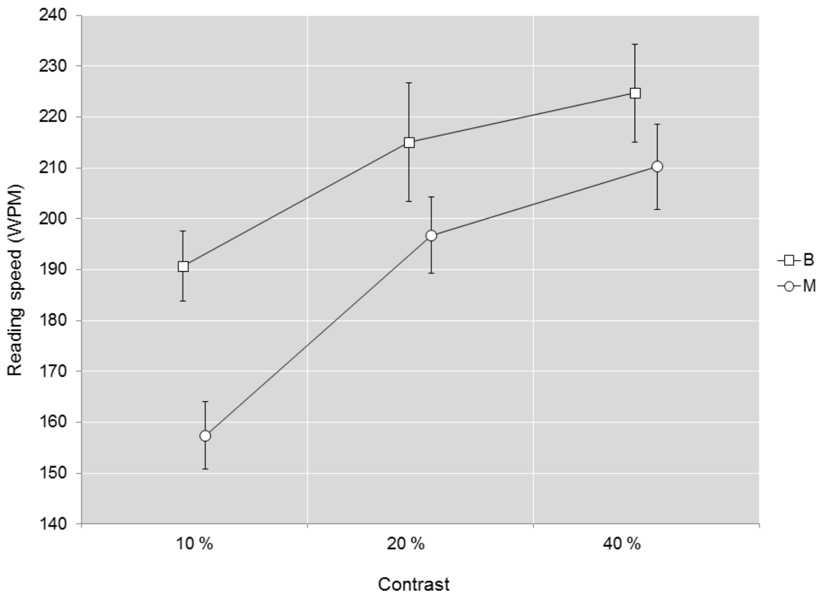


**Figure 5**. Binocular (squares) and monocular (circles) reading speed at the three levels of contrast. Error bars represent the standard error of the mean.

There was however a statistically significant main effect of viewing condition, $F\ (1, 17) = 22.74$, $p < 0.01$, $\eta^2_{partial} = 0.57$. The mean monocular reading speed was slower than binocular by 22 WPM. A pairwise comparison showed binocular reading speed to be significantly higher at 10% contrast ($p < 0.01$) and 20% contrast ($p < 0.02$), while it was marginally significant at 40% contrast ($p = 0.05$). A significant difference was also found in the main effect of stimulus contrast, $F\ (2, 34) = 32.44$, $p < 0.01$, $\eta^2_{partial} = 0.66$. The mean reading speed was slowed by 11.5 WPM between the 40% and 20% contrast and by 31.9 WPM between the 20% and 10% contrast level. A pairwise comparison showed significant differences between all three contrast levels, that is between 40% and 20% contrast ($p = 0.03$), between 40% and 10% ($p < 0.01$), and between 20% and 10% ($p < 0.01$).

The mean fixation duration at monocular reading compared to binocular increased by 8.5% at 40% contrast, by 6.9% at 20% contrast, and by 24.6% at 10% contrast (Figure 6). There was a statistically significant interaction effect between effects of viewing condition and stimulus contrast, $F\ (2, 34) = 14.89$, $p < 0.01$, $\eta^2_{partial} = 0.47$. Follow-up tests were conducted to explore the combined effects of viewing condition and contrast level. Tests of viewing condition within stimulus contrast showed monocular fixation duration to be significantly longer at all three contrast levels ($p < 0.01$) and thus demonstrating a general effect of viewing condition on fixation duration. Follow-up tests of the effect of contrast level within viewing condition showed significant differences for both monocular reading, $F(1.45, 24.61) = 51.95$, $p < 0.01$, $\eta^2_{partial} = 0.75$, and binocular reading, $F(2, 34) = 7.27$, $p < 0.01$, $\eta^2_{partial} = 0.30$. Pairwise comparisons of stimulus contrast within the monocular viewing condition showed fixation durations at 10% contrast to be significantly longer compared to both 20% and 40% contrast ($p < 0.01$). Within the binocular viewing condition the pairwise comparisons showed fixation durations at 40% contrast to be significantly shorter than both 20% and 10% contrast ($p < 0.01$). The interaction effect thus turned out as significantly increased fixation duration between 10% and 20% contrast during monocular reading, while the fixation duration was maintained during binocular reading. Secondly, the fixation duration during binocular reading was significantly reduced between 20% and 40% contrast, while it did not change significantly during monocular reading.

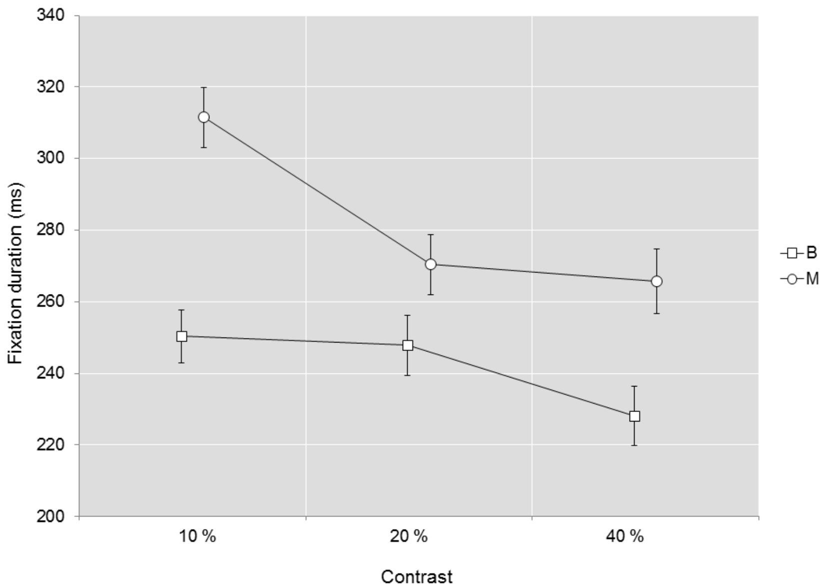


**Figure 6**. Binocular (squares) and monocular (circles) fixation duration at the three levels of contrast. Error bars represent the standard error of the mean.

For progressive saccade length there was no significant interaction effect (Figure 7). The two-way repeated measures ANOVA did however indicate a significant main effect of viewing condition, $F(1, 17) = 4.95$, $p = 0.04$, $\eta^2_{partial} = 0.23$. The mean monocular saccade length was 0.2 characters longer than binocular. In the main effect of contrast there was a significant difference, $F(2, 34) = 19.72$, $p < 0.01$, $\eta^2_{partial} = 0.54$. The saccade length at 20% contrast was significantly prolonged compared to 10% contrast ($p < 0.01$) and also at 40% contrast compared to 10% ($p < 0.01$).

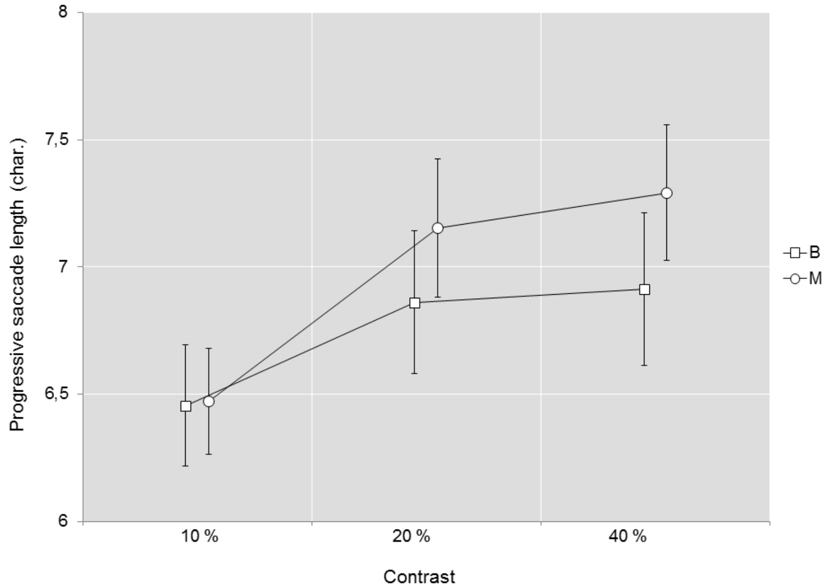


**Figure 7**. Binocular (squares) and monocular (circles) progressive saccade length (character spaces) at the three levels of contrast. Error bars represent the standard error of the mean.

The mean proportion of regressive saccades at monocular reading was 0.19±0.06 at 10% and 20% contrast and 0.18±0.05 at 40% contrast. At binocular reading the proportions were 0.19±0.05, 0.18±0.05, and 0.19±0.06 at 10%, 20%, and 40% contrast, respectively. The statistical analysis revealed no significant interaction effects or differences in main effects.

The comprehension scores in the monocular condition were 94.4±0.1%, 95.8±0.1%, and 93.7±0.1% at 10%, 20%, and 40% contrast, respectively. In the binocular viewing condition the scores were 94.4±0.1%, 95.8±0.1%, and 95.8±0.1%, respectively. A Friedmann ANOVA showed no significant differences.

### 4.2.2 Dominant versus non-dominant eye performance

Irrespective of dominance determined at distance or near, there were no statistically significant interaction effects or differences in main effects in reading performance between dominant and non-dominant eye. Nor did pairwise comparisons within condition and contrast show any significant differences. Consequently, the pattern when comparing dominant and non-dominant eye separately to binocular showed results similar to the comparison between averaged monocular performance versus binocular.

## 4.3 PAPER III

### 4.3.1 Hole-in-the-card-test

The hole-in-the-card test was repeated three times and each subject gave consistent responses. Twenty-one subjects (65.6%) were right eye dominant and 11 subjects (34.4%) were left eye dominant.

### 4.3.2 The binocular sighting test

#### *4.3.2.1 The baseline projection center*

Most subjects made a two-step positioning before settling on the baseline position. The readings of the actual projection center with plane glass in front of RE and LE were averaged to give the BPC value. Based on this, 18 subjects (56.3%) had a BPC located on the right hand side of the midline, 13 subjects (40.6%) had their BPC located on the left hand side and one subject (3.1%) had the BPC located on the midline (Figure 8).

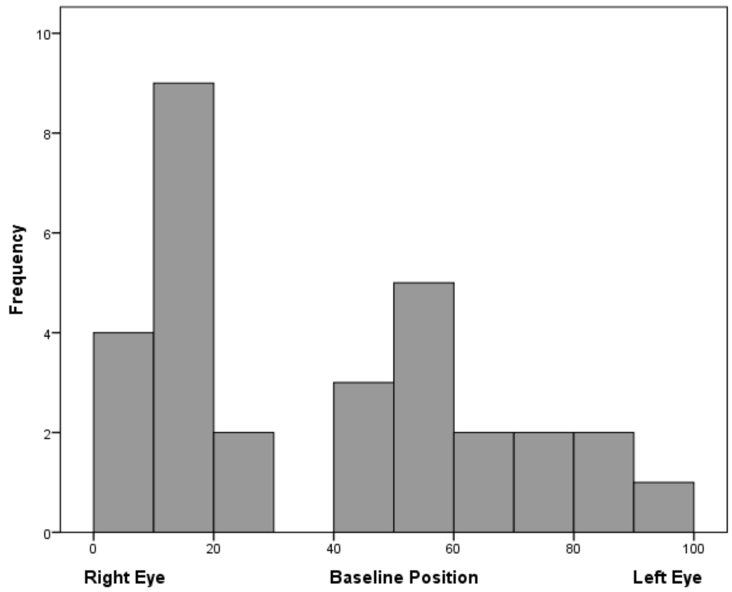


**Figure 8**. Distribution of the baseline response in the binocular sighting test.

#### *4.3.2.2 Effects of induced blur*

Some characteristic response patterns were observed (type I-IV) (Figure 9-11). The type I response pattern was observed in 20 subjects (62.5%). These subjects showed a clear preference at baseline (F0), with the actual projection points located closer to one of the eyes. The projection point remained more or less unaffected as blur was stepwise induced to the contralateral eye. On the other hand, the first step of blur induced to the ipsilateral eye of the projection point caused a major change.

The type II pattern was observed in four subjects (12.5%). In this case the actual projection point immediately changed to opposite side of midline as step one of the filter bar (F0, plane glass) was held in front of one eye. The altered projection point then stayed in this position as further blur was added. The same pattern occurred regardless of which eye was tested.

The type III response pattern was found in six subjects (18.8%). In this case the positioning meant that the actual projection point was on the same side as the eye in front of which the bar was held. As blur was induced to one eye, the subjects made a stepwise shift of the projection point towards the opposite eye.

The fourth pattern (type IV, not shown in graph) was observed in two subjects (6.2%). The projection point was in these subjects located close to one particular eye, regardless of which eye the blur was induced to.

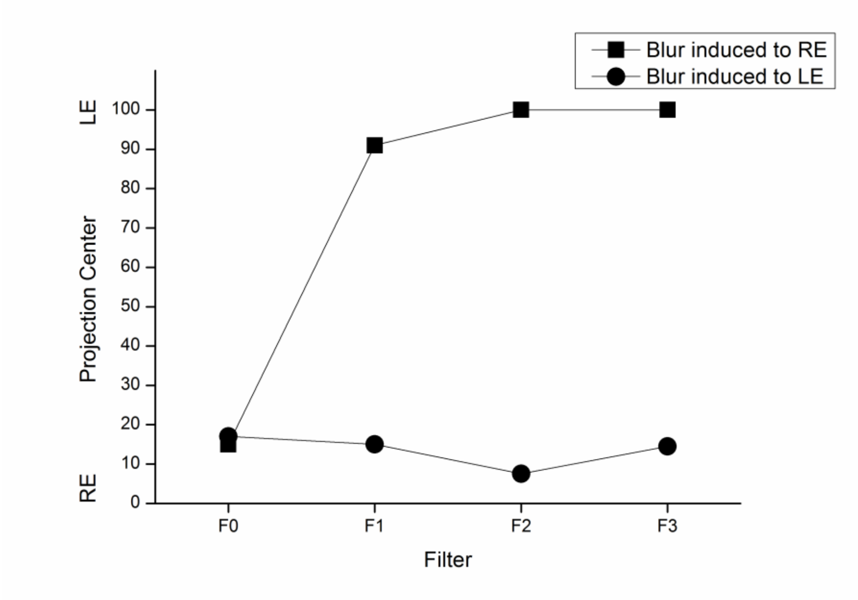


**Figure 9**. Type I response pattern due to induced blur in the binocular sighting test.

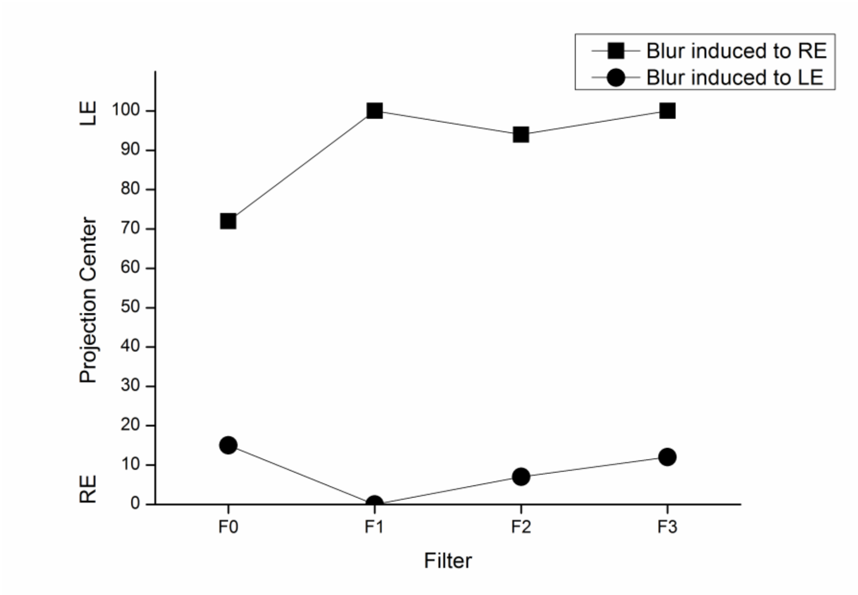


**Figure 10**. Type II response pattern due to induced blur in the binocular sighting test.

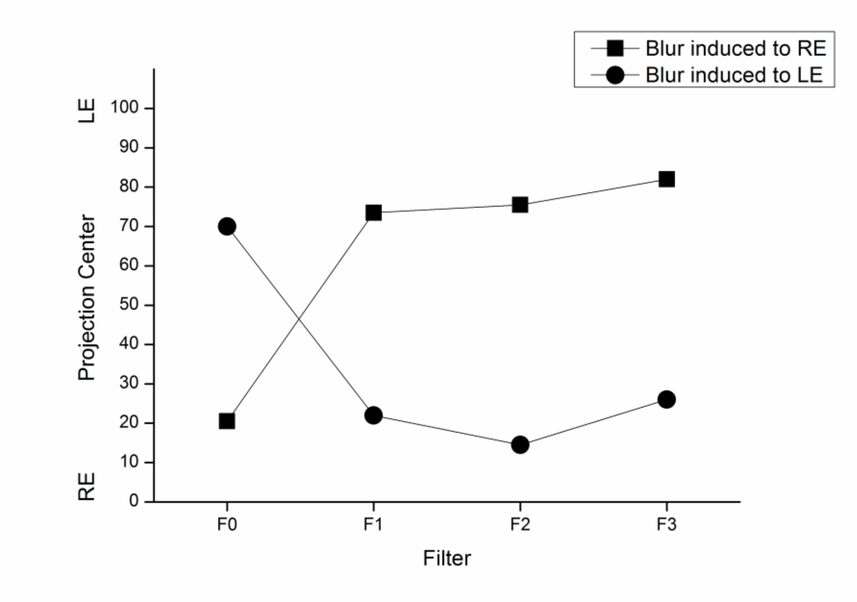


**Figure 11**. Type III response pattern due to induced blur in the binocular sighting test.

A pattern emerged in the analysis of the baseline projection center versus absolute change due to induced blur. The further the baseline projection center was located towards either eye, the greater the change in projection center when inducing blur to the ipsilateral eye, and the lesser the change, when inducing blur to the contralateral eye (Figure 12-14). A two-way repeated measures ANOVA was conducted with eye and filter as independent variables and the absolute change, in scale steps, as dependent variable. A statistically significant interaction effect was found between the effects of eye and filter (df = 2, F = 6.69, $p < 0.01$). A Pearson correlation analysis of BPC versus absolute change in projection center showed a statistically significant correlation for all three filter grades; F1 ($r = -0.513$, $p < 0.01$), F2 ($r = -0.538$, $p < 0.01$) and F3 ($r = -0.535$, $p < 0.01$).

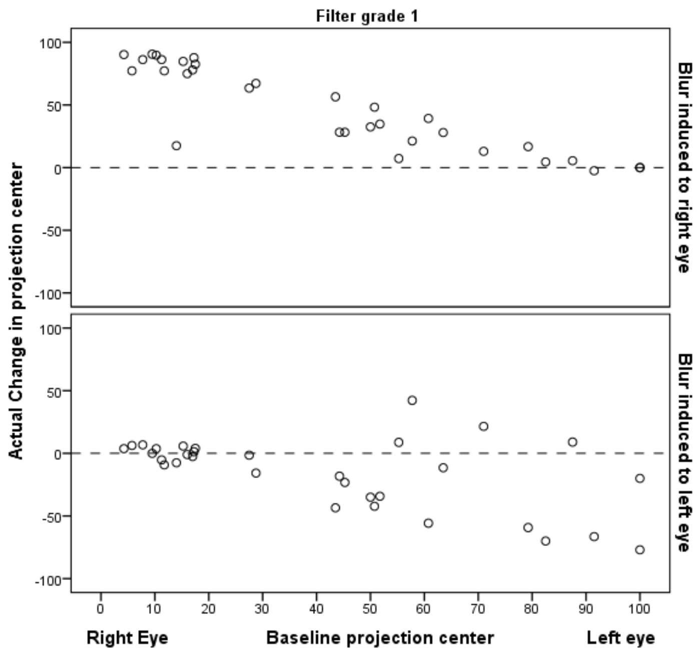


**Figure 12**. Filter grade F1. Scatter plot by filter grade (F1-F3) of basline projection center (x-axis) versus the absolute change (y-axis) from the BPC. The plots in the upper panels refers to the change as blur is induced to the right eye and the lower panels show the corresponding plot when blur is induced to the left eye.

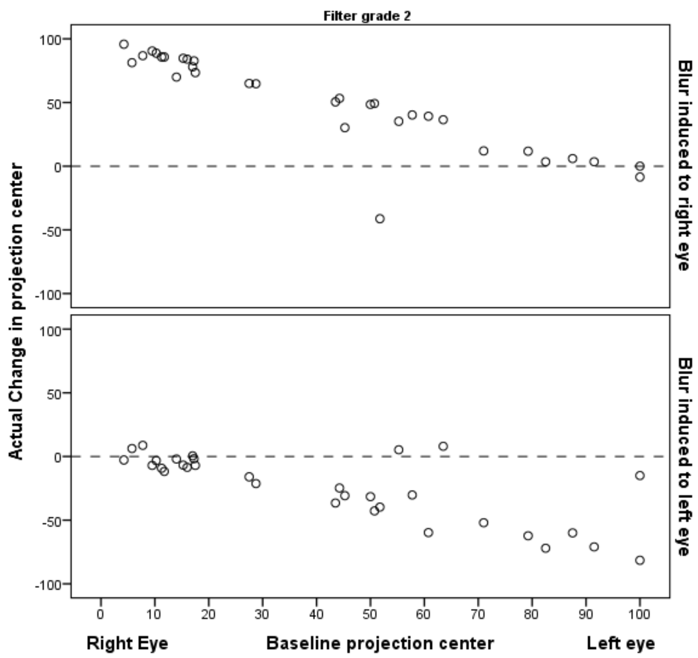


**Figure 13**. Filter grade F2.

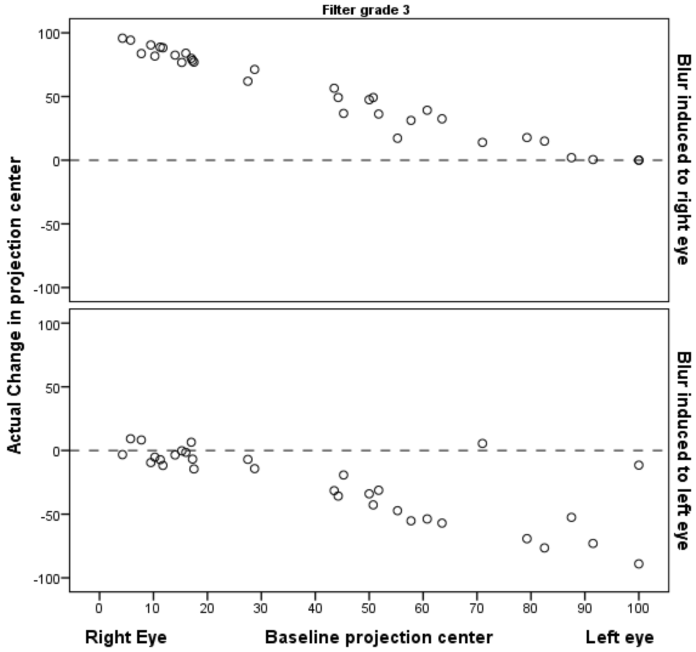


**Figure 14**. Filter grade F3.

### 4.3.3 The variable angle mirror test

#### *4.3.3.1 The baseline response*

The responses with plane glass in front of left and right eye respectively were averaged to give the baseline. The baseline response was scored as -1 if the response was left eye preference at both trials, e.g. (-1 + (-1))/2, a score of 1 if right eye preference at both trials, e.g. (1+1)/2, or a score of ±0.5 if no preference at one trial and left or right preference at the other, e.g. (0+1)/2. In case of no preference at either trial the score was set to 0.

Eighteen subjects (56.3%) showed right eye preference, five subjects (15.6%) left eye preference and nine subjects (28.1%) showed no preference.

#### *4.3.3.2 Effects of induced blur*

The sample subject below (Figure 15) shows an example of pronounced right eye dominance. The subject's baseline response was right eye dominance. Two steps of induced blur was required on the right eye to cause a release of the partial suppression of left eye, meaning that the subject reported to see two faint images of the hinge, one covering each eye. As one more step of blur was induced to right eye, partial suppression occurred to the right eye meaning that the subject perceived the hinge to cover left eye. The left eye, on the other hand, was partially suppressed from the beginning. Thirteen subjects (40.6%) showed a similar right eye preference pattern and two subjects (6.2%) showed the corresponding left eye preference pattern. In subjects with a less pronounced dominance (11 subjects, 34.4%) (Figure 16), a slight relative difference in tendency to suppress blur could still be observed. Subjects with no preference at baseline (6 subjects, 18.8%) (Figure 17) showed a symmetric left and right eye pattern of blur suppression.

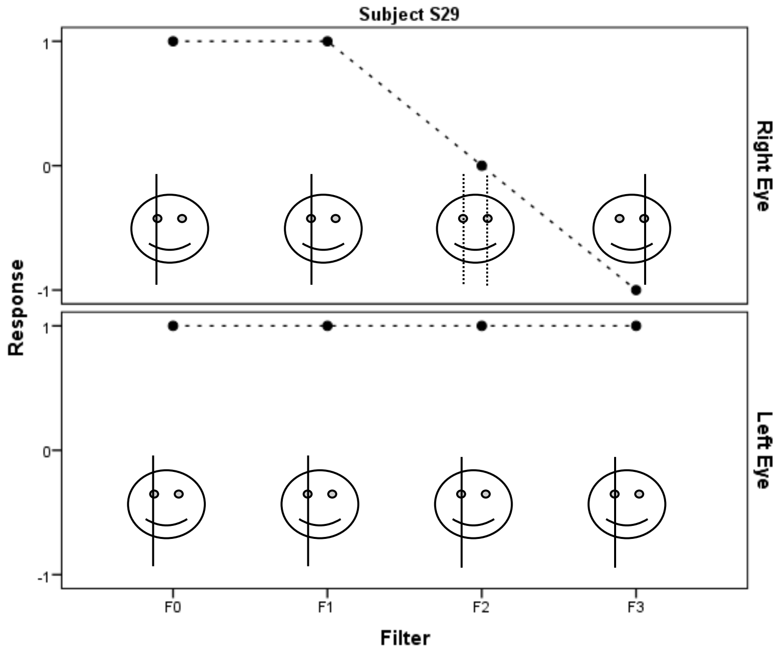


**Figure 15**. Pronounced right eye preference. The upper panel shows result of inducing blur to the right eye and the lower panel when inducing blur to the left eye. The value 1.0 on y-axis means that the subject perceived that right eye was covered by the hinge while the value -1.0 means that hinge was perceived to cover left eye. A value of 0 means the subject perceived two images of the hinge, one covering each eye.

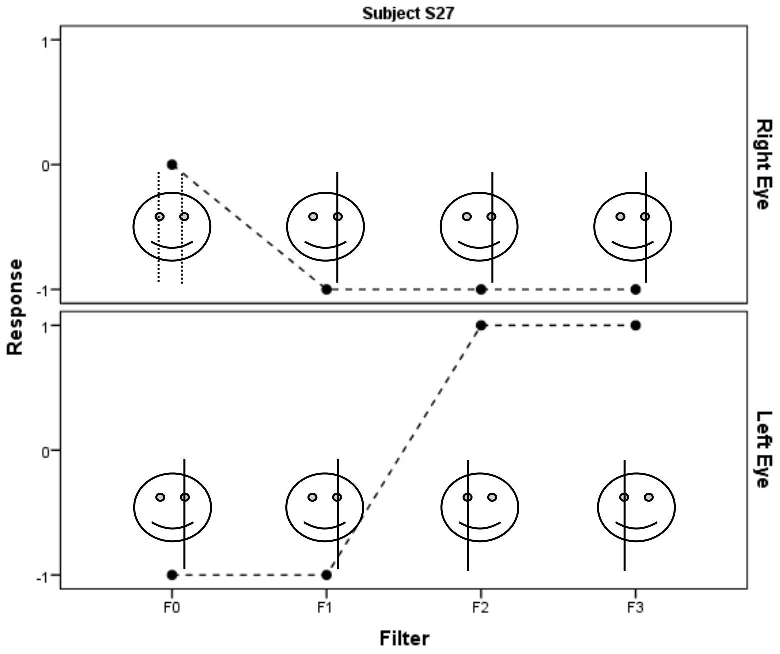


**Figure 16**. Less pronounced eye preference with a slight weighting towards the left eye. A relative difference in sensitivity to blur can be observed where two increments of blur to left eye versus one step to the right eye were required to transfer the percept.

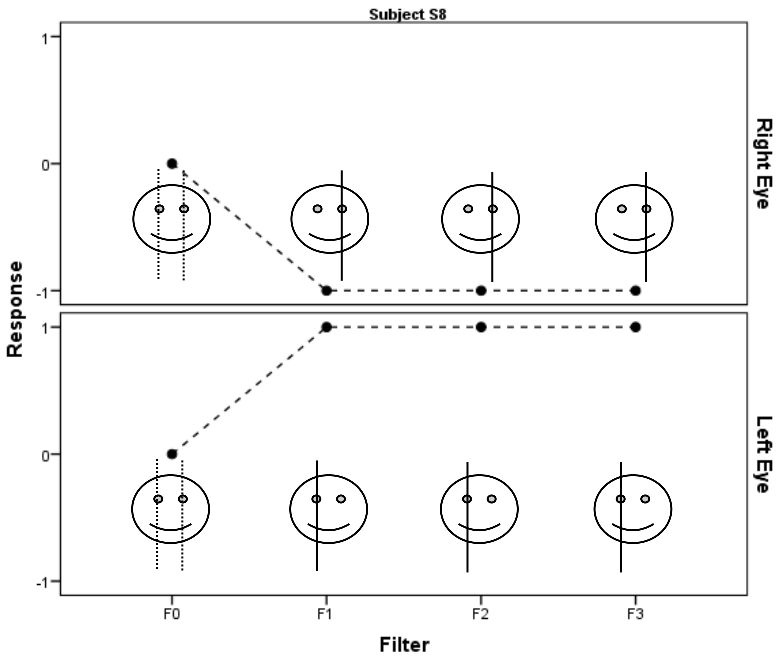


**Figure 17**. No eye preference at baseline and a similar sensitivity to blur for each eye.

The interocular difference in number of filter steps required to alter the baseline response was calculated. This was done by subtracting the number of steps required for LE from the number of steps required for RE. The result was zero in case of no difference. In case of RE requiring more steps of blur the value was positive in the range of 1-3. In case of LE requiring more steps the value was negative in the same range. A spearman correlation analysis of the baseline response, versus the interocular difference in blur required to transfer suppression, showed a significant correlation ($r = 0.75$, $p < 0.01$).

### 4.3.4 Correlation between tests

#### *4.3.4.1 BST versus HICT*

The correlation between BPC and HICT was weak ($r = 0.18$, ns). One third of subjects with RE dominance according to the HICT, and 45.5% of subjects with LE dominance, showed the opposite behavior in BPC (Figure 18).

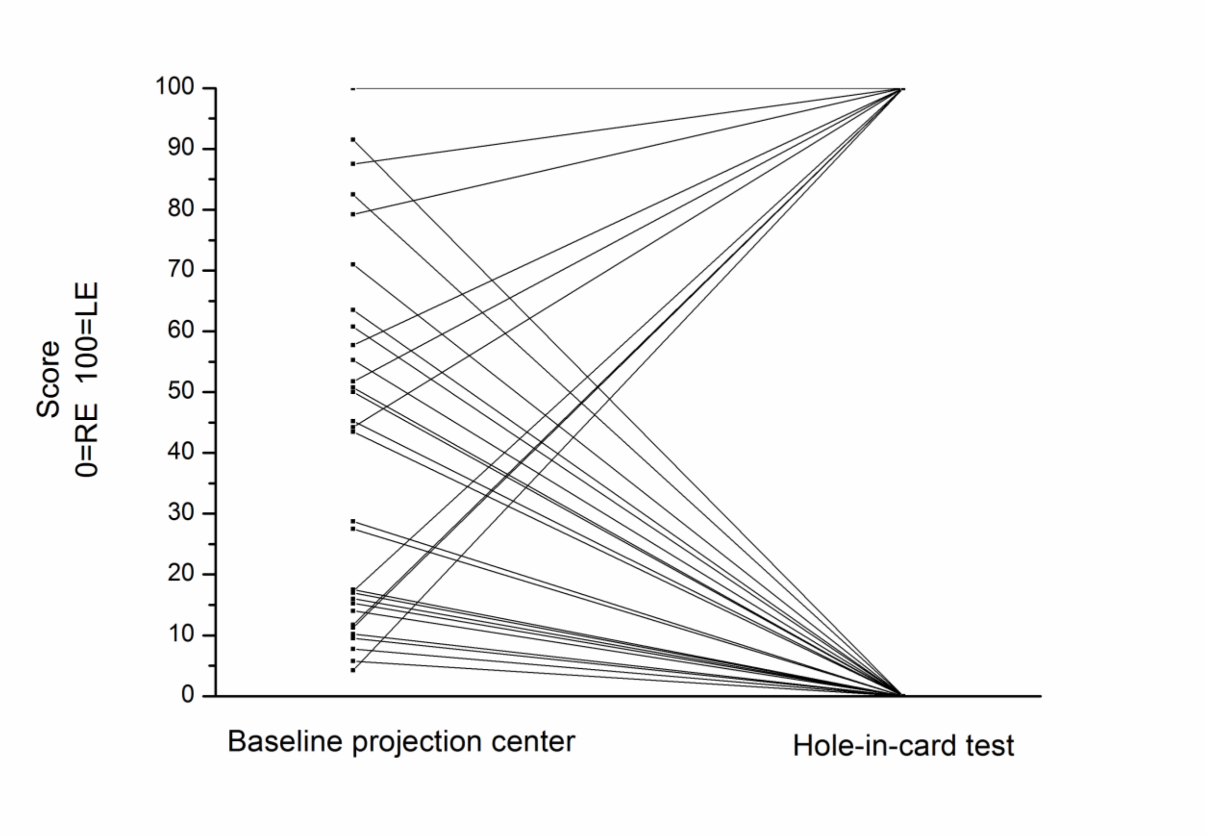


**Figure 18**. BPC versus sighting dominance (HICT).

#### *4.3.4.2 VAMT versus HICT*

The correlation with the HICT was moderate ($r = 0.527$, $p < 0.01$). Twenty subjects (62.5%) showed an agreement with the HICT, nine subjects (28.1%) showed no preference and three subjects (9.5%) showed opposite dominance (Figure 19).

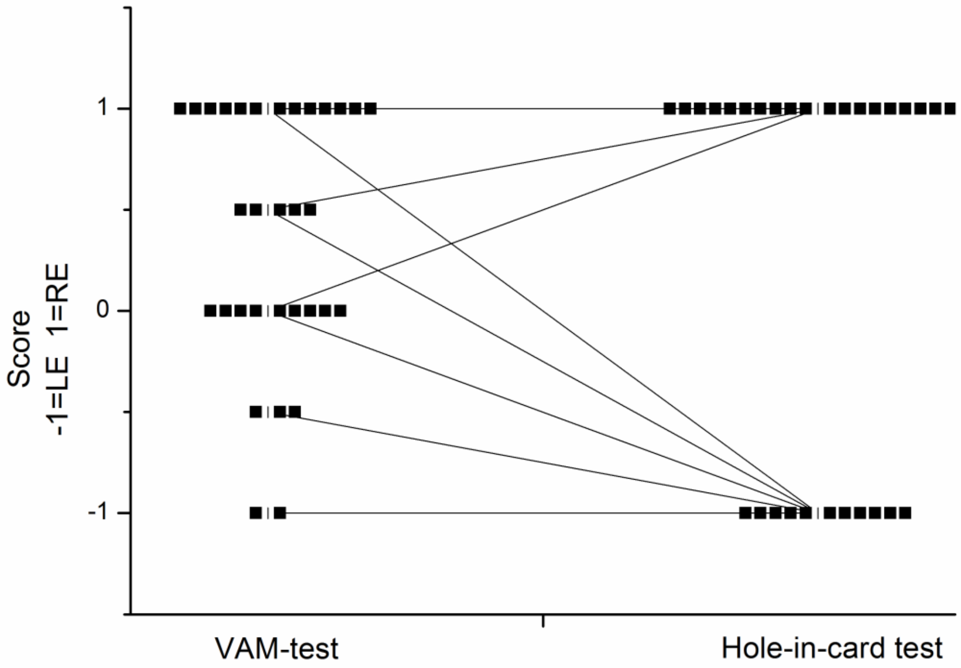


**Figure 19**. VAM-test versus Hole-in-the-card-test.

*4.3.4.3 BST versus VAMT*

The correlation between BST and VAMT on total group level was weak (r = 0.16, n.s.). A total of 22 subjects (68.8%) showed an eye preference in both tests. These 22 subjects were divided into a group of 14 subjects, who showed an agreement between BST and VAMT, and a group of eight, who did not show an agreement. For the group of 14 there was a significant correlation between baseline responses of BST and VAMT (n = 14, r = -0.61, p = 0.02). There was also an almost complete agreement (92.9%) with the HICT. For the group of eight there was no significant correlation between baseline responses of BST and VAMT. The result of HICT agreed better with the VAMT in this group (75.0%).

## 4.4 PAPER IV

### 4.4.1 Visual symptoms at near work

The CISS score before treatment was missing for one patient (S6). The symptom assessment according to CISS for the remaining seven patients revealed a mean score of 37.9±7.3 before treatment and 26.0±5.7 after treatment (n=7). The difference was statistically significant (p = 0.02). Two patients (S4 and S5) scored as asymptomatic (≤21) after treatment (Figure 20). Another two patients (S2 and S8) showed a considerable reduction in symptom score.

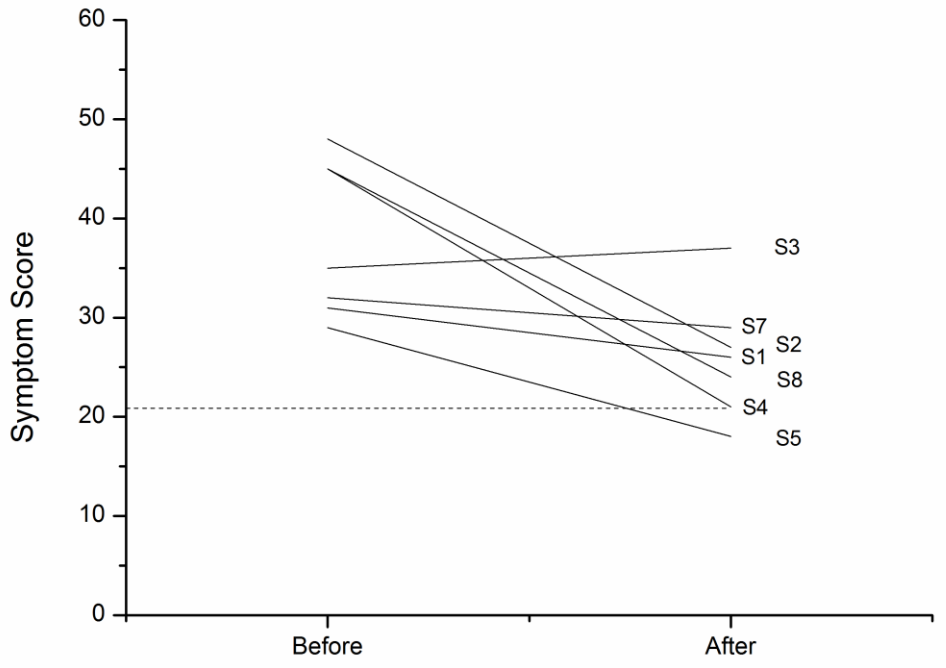


**Figure 20**. Individual symptom score before and after treatment. The dotted line indicates the total score limit for being asymptomatic (≤21).

The score for each item in the CISS form was averaged on group level and plotted to visualize the symptom profile before and after treatment (Figure 21). For reference the plot includes results from two previous studies that assessed symptoms in patients with blast induced mild traumatic brain injury (Capo-Aponte et al., 2012) and in healthy subjects with normal vision (J. Johansson et al., 2014b). A similarity in profile could be observed between the patient populations of the current study and the study by Capo Aponte et al. In the current study the profile remained after treatment however with a general reduction of symptoms. Notably, the specific visual symptoms of blurred or double vision did not stand out.

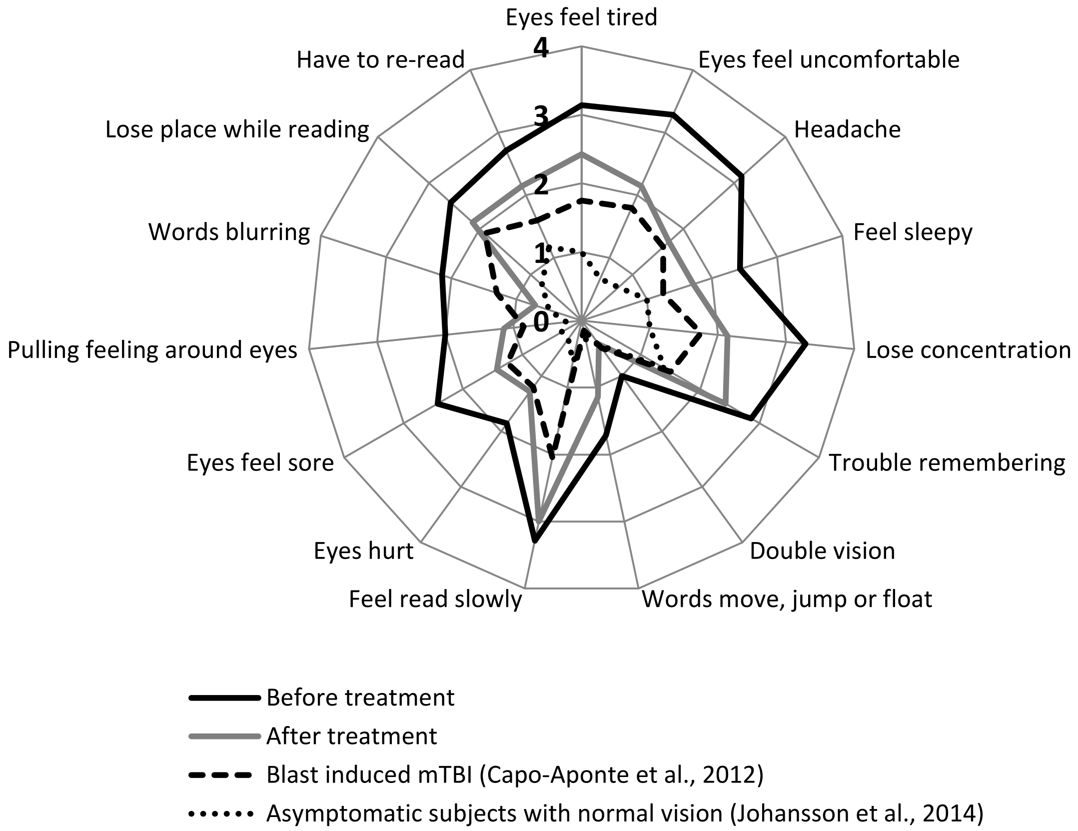


**Figure 21**. Symptom profile based on averaged CISS score by item.

### 4.4.2 Visual functions

All patients had a good corrected visual acuity. The findings in the visual examination (Table 2) included accommodative deficits showing as reduced accommodative amplitude with or without affected accommodative facility. Furthermore, in four patients the vergence was affected and showing as a receded near point of convergence, high exophoria or an affected fusional vergence range. One patient had uncorrected hyperopia.

At the follow-up examination two patients (S2, S8) showed an increase (improvement) in accommodative amplitude but did not reach the normal expected span. One patient (S4) showed a reduction (worsening) in accommodative amplitude. The receded near point of convergence had normalized in two patients (S2 and S4). The fusional vergence range increased in one patient (S5). No significant correlations were found between reduction in visual symptoms and improved visual clinical measures, however those patients who showed a decreased symptom score also tended to improve in at least one clinical measure.

**Table 2** Clinical measures.

| Patient | Age | Clinical finding | Prescription | Clinical measures Before | After | Improved | Comments by subject |
|---|---|---|---|---|---|---|---|
| **S1** | 34 | Reduced AA | Office progressives<br>Refraction plus add +1.00 D | 7.1 D | 5.7 D | No | Possible to read for longer period<br>Still avoids recreational reading<br>Less frequent headaches |
| **S2** | 36 | Reduced AA<br>Receded NPC<br>High exophoria<br>Reduced PFV | Single vision<br>Refraction plus add +1.00 D<br>Prism 4 prd base in | 2.5 D<br>20 cm<br>16 Prd BI<br>20 Prd BO | 4.8 D<br>8 cm<br>10 Prd BI<br>18 Prd BO | Yes<br>Yes<br>Yes<br>No | Less headache during near work<br>Still slow reading<br>Easier to alter focus near - intermediate |
| **S3** | 24 | Marginally reduced AA | Single vision<br>RE/LE +1.00 D | 10.5 D | 10.0 D | No | Reading more calm and restful<br>Still slow reading<br>Still difficulty with line transition<br>Still frequent headaches |
| **S4** | 31 | Reduced AA<br>Marginally receded NPC | Office progressives<br>Refraction plus add +1.00 D | 7.4 D<br>11 cm | 4.5 D<br>5 cm | No<br>Yes | Less fatigue and headache<br>No floating words |
| **S5** | 56 | Presbyopia<br>High exophoria<br>Reduced PFV | Single vision<br>Refraction plus add +2.00 D<br>Prism 2 prd base in | 14 Prd BI<br>25 Prd BO | 14 Prd BI<br>30 Prd BO | No<br>Yes | Improved perseverence and comprehension<br>Still slow reading<br>Still daily headaches |
| **S6** | 24 | Reduced AA | Single vision<br>RE/LE +1.00 D | 9.1 D | 8.3 D | No | Improved perseverence<br>Less floating words<br>Still daily headaches<br>Still frequent headaches |
| **S7** | 37 | High exophoria<br>Reduced PFV | Single vision<br>Refraction plus add +1.00 D<br>Prism 3 prd base in | 10 Prd BI<br>18 Prd BO | 16 Prd BI<br>16 Prd BO | No<br>No | Reading more restful<br>Text more clear<br>Still difficult to concentrate<br>Still skipping words |
| **S8** | 21 | Hyperopia<br>Reduced AA | Single vision<br>Refraction plus add +0.50 D | 6.7 D | 8.7 D | Yes | No pulling sensation in eyes<br>Improved perseverance and comprehension<br>Text more clear<br>Less frequent headache (once weekly vs daily)<br>Still slow reading |

AA: Accommodative Amplitude; BI: Base In; BO: Base Out; D: Diopter; NPC: Near Point of Convergence; PFV: Positive Fusional Vergence; Prd: Prism diopter

### 4.4.3 Reading performance

Reading eye movement data was complete for six patients. The mean binocular reading speed increased from 214.3±32.1 to 246.9±57.1 after treatment (Table 3). This corresponded to an increase by 15.2% which was not statistically significant. Reading was still slower with more fixations, higher fixation duration and shorter saccades as compared to a reference group. The comparison of binocular and monocular reading performance at the second examination showed monocular reading speed (217.6±45.1) to be 11.9 % slower than binocular (246.9±57.1). The difference was marginally significant ($p = 0.05$).

**Table 3**. An overview of binocular and monocular reading performance. The monocular performance was compared to binocular after spectacle treatment.

| | **Binocular reading performance** | | | **Monocular reading performance** | | **Reference group*** | |
|---|---|---|---|---|---|---|---|
| **Measure** | **Before** | **After** | **Change (%)** | **Monocular** | **Difference vs binocular (%)** | **Binocular** | **Monocular** |
| WPM | 214.3±32.1 | 246.9±57.1 | +15.2 | 217.6±45.1 | -11.9 | 269.6±33.5 | 264.2±36.3 |
| Fixations per word | 1.17±0.15 | 1.07±0.13 | -8.5 | 1.22±0.20 | +14.0 | 0.96±0.11 | 0.94±0.13 |
| Fixation duration (ms) | 200.6±21.4 | 199.5±48.1 | -0.5 | 182.1±35.4 | -8.7 | 187.4±23.5 | 204.0±29.2 |
| Progressive saccade length (char.) | 5.1±1.0 | 5.2±0.9 | +2.0 | 6.1±1.2 | +17.3 | 7.4±0.9 | 7.4±1.0 |
| Proportion of regressive saccades | 0.19±0.03 | 0.22±0.06 | +15.8 | 0.25±0.08 | +13.6 | 0.2±0.1 | 0.2±0.1 |

***** *Reference group: 18 healthy subjects with normal binocular vision (J. Johansson et al., 2014b)*

The change in binocular reading performance on group level before and after treatment was due to four subjects (S1, S4, S5, S6) who increased their reading speed by 10.7-48.5% (Table 4). The increase in reading speed was accompanied by an improved reading efficiency, visible in reduced number of fixations (9.4-20.9%), shortened fixation duration (7.7-23.5%) and lengthened progressive saccades (2.0-24.3%).

**Table 4**. Binocular reading performance before and after treatment.

| | Symptom score | | | Binocular reading performance | | | | |
|---|---|---|---|---|---|---|---|---|
| **Subject** | **Before** | **After** | **Reduced** | **Measure** | **Before** | **After** | **Change (%)** | **Improved** |
| **S1** | 31 | 26 | No | WPM | 187.3±1.9 | 252.6±22.5 | +34.9 | Yes |
| | | | | Fixations per word | 1.38±0.16 | 1.25±0.07 | -9.4 | |
| | | | | Fixation duration (ms) | 198.7±134.7 | 152.1±85.9 | -23.5 | |
| | | | | Progressive saccade length (char.) | 3.7±2.3 | 4.6±3.3 | +24.3 | |
| | | | | Proportion of regressive saccades | 0.20±0.02 | 0.20±0.03 | ±0 | |
| **S4** | 45 | 21 | Yes | WPM | 260.5±16.1 | 305.6±6.2 | +17.3 | Yes |
| | | | | Fixations per word | 0.97±0.01 | 0.97±0.12 | ±0 | |
| | | | | Fixation duration (ms) | 206.6±111.3 | 161.6±77.4 | -21.8 | |
| | | | | Progressive saccade length (char.) | 5.7±3.3 | 6.4±3.4 | +12.3 | |
| | | | | Proportion of regressive saccades | 0.20±0.04 | 0.20±0.06 | ±0 | |
| **S5** | 29 | 18 | Yes | WPM | 247.5±21.4 | 274.0±17.4 | +10.7 | Yes |
| | | | | Fixations per word | 1.11±0.17 | 0.99±0.10 | -10.8 | |
| | | | | Fixation duration (ms) | 190.0±86.8 | 165.7±81.0 | -12.8 | |
| | | | | Progressive saccade length (char.) | 6.5±3.9 | 6.2±4.3 | -4.6 | |
| | | | | Proportion of regressive saccades | 0.22±0.02 | 0.27±0.10 | +22.7 | |
| **S6** | - | 33 | - | WPM | 196.7±1.0 | 292.1±52.2 | +48.5 | Yes |
| | | | | Fixations per word | 1.15±0.08 | 0.91±0.23 | -20.9 | |
| | | | | Fixation duration (ms) | 213.9±121.8 | 197.5±104.5 | -7.7 | |
| | | | | Progressive saccade length (char.) | 5.0±2.8 | 5.1±3.1 | +2.0 | |
| | | | | Proportion of regressive saccades | 0.13±0.01 | 0.12±0.01 | -7.7 | |
| **S7** | 32 | 29 | No | WPM | 184.8±3.9 | 159.9±7.4 | -13.5 | No |
| | | | | Fixations per word | 1.29±0.12 | 1.15±0.01 | -10.9 | |
| | | | | Fixation duration (ms) | 166.1±124.2 | 289.3±142.9 | +74.2 | |
| | | | | Progressive saccade length (char.) | 4.8±2.4 | 4.0±3.7 | -16.7 | |
| | | | | Proportion of regressive saccades | 0.17±0.00 | 0.25±0.07 | +47.1 | |
| **S8** | 45 | 24 | Yes | WPM | 208.6±10.4 | 197.3±0.5 | -5.4 | No |
| | | | | Fixations per word | 1.11±0.08 | 1.12±0.00 | +0.9 | |
| | | | | Fixation duration (ms) | 228.2±107.8 | 230.8±95.0 | +1.1 | |
| | | | | Progressive saccade length (char.) | 4.7±2.6 | 5.3±3.1 | +12.8 | |
| | | | | Proportion of regressive saccades | 0.19±0.01 | 0.26±0.00 | +36.8 | |

The binocular advantage in reading speed on individual level was calculated by subtracting individual binocular reading speed from monocular (Table 5). All patients showed a binocular advantage where binocular reading was between 2.7% and 38.6% (mean 13.5%) faster. The difference in reading speed was associated with differences in reading eye movements. For the subjects (S1, S8) showing a low to moderate binocular advantage in reading speed (2.7-6.8%) it was mainly associated with a reduced number of fixations. For the subjects (S4, S5, S6, S7) who showed a higher binocular advantage (10.8-38.6%) it was associated with more pronounced reductions in number of fixations and proportion of regressive saccades.

**Table 5**. Binocular versus monocular reading performance.

| Subject | Measure | Binocular | Monocular | Difference (%) | Outcome |
|---|---|---|---|---|---|
| **S1** | WPM | 252.6±22.5 | 245.9±6.3 | +2.7 | Marginal binocular advantage |
| | Fixations per word | 1.25±0.07 | 1.32±0.08 | -5.3 | |
| | Fixation duration (ms) | 152.1±85.9 | 138.2±71.6 | +10.1 | |
| | Length of progressive saccades (char.) | 4.6±3.3 | 4.5±2.6 | +2.2 | |
| | Proportion of regressive saccades | 0.20±0.03 | 0.15±0.05 | +33.3 | |
| **S4** | WPM | 305.6±6.2 | 220.5±13.5 | +38.6 | Binocular advantage |
| | Fixations per word | 0.97±0.12 | 1.25±0.33 | -22.4 | |
| | Fixation duration (ms) | 161.6±77.4 | 149.6±84.4 | +8.0 | |
| | Length of progressive saccades (char.) | 6.4±3.4 | 5.4±3.4 | +18.5 | |
| | Proportion of regressive saccades | 0.20±0.06 | 0.26±0.01 | -23.1 | |
| **S5** | WPM | 274.0±17.4 | 247.4±46.9 | +10.8 | Binocular advantage |
| | Fixations per word | 0.99±0.10 | 1.19±0.18 | -16.8 | |
| | Fixation duration (ms) | 165.7±81.0 | 168.1±84.9 | -1.4 | |
| | Length of progressive saccades (char.) | 6.2±4.3 | 7.3±4.5 | -15.1 | |
| | Proportion of regressive saccades | 0.27±0.10 | 0.29±0.05 | -6.9 | |
| **S6** | WPM | 292.1±52.2 | 262.6±49.8 | +11.2 | Binocular advantage |
| | Fixations per word | 0.91±0.23 | 0.86±0.02 | +5.8 | |
| | Fixation duration (ms) | 197.5±104.5 | 180.2±103.3 | +9.6 | |
| | Length of progressive saccades (char.) | 5.1±3.1 | 7.4±4.1 | -31.1 | |
| | Proportion of regressive saccades | 0.12±0.01 | 0.18±0.03 | -33.3 | |
| **S7** | WPM | 159.9±7.4 | 144.3±13.8 | +10.8 | Binocular advantage |
| | Fixations per word | 1.15±0.01 | 1.47±0.18 | -21.8 | |
| | Fixation duration (ms) | 289.3±142.9 | 233.6±143.3 | +23.8 | |
| | Length of progressive saccades (char.) | 4.0±3.7 | 5.0±4.7 | -20.0 | |
| | Proportion of regressive saccades | 0.25±0.07 | 0.38±0.02 | -34.2 | |
| **S8** | WPM | 197.3±0.5 | 184.8±20.3 | +6.8 | Binocular advantage |
| | Fixations per word | 1.12±0.00 | 1.21±0.02 | -7.4 | |
| | Fixation duration (ms) | 230.8±95.0 | 222.8±110.8 | +3.6 | |
| | Length of progressive saccades (char.) | 5.3±3.1 | 6.8±3.7 | -22.1 | |
| | Proportion of regressive saccades | 0.26±0.00 | 0.27±0.01 | -3.7 | |

# 5 DISCUSSION

The discussion will in turn deal with the binocular advantage in reading, the role of eye dominance in reading, eye dominance under binocular viewing conditions and the effect of spectacle treatment in patients with MTBI. Plausible mechanisms will be discussed in relation to the findings in these studies and previous research.

## 5.1 THE BINOCULAR ADVANTAGE IN IN READING

In papers I and II, monocular and binocular reading performance were compared in order to estimate the advantage of binocular vision. In addition, the relation between monocular performance and eye dominance was studied. By occluding one eye the intention was to remove any binocular advantage in terms of an acuity reserve, contrast reserve, or increased sensitivity in the visual field. On the other hand, at monocular reading the demand for binocular coordination is also removed which has been observed as a potential relief, at least in the presence of high exophoria (Jainta & Jaschinski, 2012). The stimulus consisted of texts (IReST) that have a readability index well below the expected reading ability of the participants. In paper I the stimulus was presented at high contrast (96%), a contrast level that would be expected in many day to day situations when text is presented on a computer display. In paper II the stimulus was presented at considerably reduced contrasts; 10%, 20% and 40%.

In paper I the monocular reading speed was found to be on average 2.1% slower than binocular. The difference was not statistically significant and it was smaller than found in previous studies where a difference of 5% was found when reading continuous text (Kanonidou, Proudlock, & Gottlob, 2010; Robinson, 1951). The main difference in eye movements was found in increased mean fixation duration at monocular reading. This is in accordance with previous studies comparing monocular and binocular reading (Heller & Radach, 1999; Jainta & Jaschinski, 2012; Kanonidou et al., 2010). The mean number of progressive and regressive saccades did not differ significantly, nor did the mean length of saccades in general. A further detailed analysis of fixation pattern would be required to fully understand this outcome, e.g. an analysis of first fixation durations, re-fixation pattern, and effects of lexical properties such as word length and word frequency. However, if making an assumption from a broad view, that the maintenance of progressive and regressive saccade pattern was generally maintained at the cost of increased mean fixation duration, then it may suggest that the aspect of when to move rather than where to move was mainly affected. Factors that may be considered to affect this are the binocular coordination, the ability to recognize characters at point of fixation and the pre-processing of words to the right of fixation. Previous research on binocular coordination at monocular and binocular reading found changes in disconjugacy and the post-saccadic vergence drift (Jainta & Jaschinski, 2012). At monocular reading the disconjugacy after saccades increased and the vergence drift, that is expected to reduce the disconjugacy, instead became divergent relative the fixation distance. This was considered an indication that the vergence drift following reading fixations is disparity driven and, at monocular reading fixations, the vergence system works in an open loop mode. It thus appears less likely that binocular coordination had a major effect in the increased fixation duration.

In paper I the stimulus contrast was high. Any reduction in acuity due to monocular viewing would be expected to be minimal since the summation effects are small for complex stimuli at high contrast (Blake et al., 1981; Frisen & Lindblom, 1988). Furthermore, an experimental study applying degraded visibility isolated to foveal vision during reading found the fixation duration and overall reading performance to be relatively robust (Jordan, McGowan, & Paterson, 2012). If the pre-processing of words was affected at monocular viewing, e.g. due to decreased sensitivity in the visual field, then this may have contributed to the increased mean fixation duration. As noted above a more detailed analysis would be required to support this, however, a recent experiment using sentence reading at binocular and monocular conditions, found that the preprocessing of high-frequency words were inhibited, leading to prolonged first fixation duration (Jainta et al., 2014). That is, increased fixation duration for high frequency words that would normally be fixated more briefly.

In summary, the findings of a binocular advantage in paper I was minimal. Explanations to this may be found in the reading process itself where other factors such as context and reading experience play a pronounced role (Flax, 1970; Rayner, 1998). From a visual point of view, explanations may be found in the summation literature, i.e. that processing of complex stimuli presented at high contrast tend to lead to low summation effects (Blake et al., 1981; Frisen & Lindblom, 1988).

In paper II reading was done at three levels of reduced stimulus contrast. Binocular reading was significantly faster (7-21%) at all three contrast levels. The greatest binocular advantage occurred between 10% and 20% contrast where also the steeper overall reduction of reading speed occurred. The binocular reading speed has been found to decline more rapidly between 10-30% contrast in previous research (Legge et al., 1990; Legge et al., 1987). It appears that a binocular advantage may become more apparent as discrimination of the stimulus becomes more difficult. An observation also made in binocular summation studies (Banton & Levi, 1991; Bearse & Freeman, 1994; Jones & Lee, 1981; Pardhan, 2003).

Similar to in paper I, prolonged mean fixation durations at monocular reading was the most apparent difference in eye movements. The fixation durations during monocular reading were markedly longer (9-24%) than found in other studies of monocular and binocular reading (Heller & Radach, 1999; Jainta & Jaschinski, 2012; Kanonidou et al., 2010) which is likely to be due to the lower stimulus contrast. A significant interaction effect between contrast and viewing condition was found. This showed as a steeper increase of mean fixation duration with reduced contrast at monocular reading. As observed in previous research, a word frequency effect has been found explaining part of the difference in fixation duration between monocular and binocular reading (Jainta et al., 2014). Another study that explored binocular reading at reduced contrast found an interaction between contrast and word length (Legge et al., 1997). Longer words required more and longer fixations at low contrast resulting in an increased overall reading time per word. This finding was attributed to a shrinking visual span, i.e. that fewer characters could be identified at one fixation. The ability to discriminate stimulus in the periphery, particularly at low contrast, has been shown to be significantly improved at binocular viewing compared to monocular (Pardhan, 2003; Zlatkova et al., 2001). The significant interaction effect found in paper II which manifested at 10% contrast, where reading performance has been shown to fall off considerably (Legge et al., 1990; Legge et al., 1987), appear to indicate that binocular summation contributes to the robustness of reading.

In addition to fixation duration there was a significant main effect of progressive saccade length where prolonged mean length of saccades was observed at monocular reading. The effect did however diminish at 10% contrast. In previous research there have been observations of both prolonged and shortened saccades at monocular reading (Jainta & Jaschinski, 2012; Kanonidou et al., 2010). The actual mean difference was less than a character. The prolonged saccades are possibly related to saccadic dysmetria caused by the unfamiliar situation of reading with one eye. Experimental studies on the computation of saccade metrics during reading have indicated that the computation is based on a unified percept of the oculocentric signals (Liversedge, Rayner, et al., 2006). The occlusion of one eye possibly interferes with this process. The current experiment applied monocular reading at an un-adapted state. There are indications that the difference between monocular and binocular performance lessens following a few days of monocular occlusion (Sheedy et al., 1986).

The estimated reading comprehension did not differ significantly between any of the reading conditions. At present there is no other study to compare this outcome to. However, other studies have found comprehension to be quite robust in reading conditions that are more difficult, e.g. due to blur or reduced spatial frequency (Jainta et al., 2011; Jordan et al., 2012).

## 5.2 EYE DOMINANCE AND READING

In paper I the agreement between eye dominance and faster reading speed was 44 or 56% depending on the method to determine dominance. However, the differences between dominant and non-dominant eye were small. With dominance determined at 4 m there were no significant differences for any of the reading performance measures. With dominance determined at near a slightly increased mean saccade length was observed for the non-dominant eye. In paper II no significant differences in performance were found, regardless of the method to determine eye dominance. Previous studies involving subjects with normal vision did not find any significant differences related to dominance either (Jainta & Jaschinski, 2012; Kanonidou et al., 2010; Robinson, 1951). If there is an asymmetry in motor functioning related to eye dominance (Walls, 1951) then a difference in reading performance between dominant and non-dominant eye might be expected. A study of conjugate eye movements at reading distance found indications of higher saccade velocity for dominant eye (20-25 °/s), but no significant difference in latency (< 8ms) between dominant and non-dominant eye (Oishi et al., 2005). Considering the small magnitude of these differences it is possible that differences in performance related to eye dominance occurred in paper I and II but was not detected. Another explanation to the weak relation between eye dominance and performance in the present study may be related to the task itself. A study of convergence responses to stimulus moving in depth found significant differences related to eye dominance (Kawata & Ohtsuka, 2001). The mean peak velocity of the fusion-initiating, fast, component of the vergence response was greater in the dominant eye along with a shorter latency for the fusion-sustaining, slow, component. Another study compared the vergence dynamics in pure vergence-, combined version-vergence-, and reading tasks and found quicker and more accurate target fixation with the dominant eye in the pure vergence task (van Leeuwen et al., 1999). More accurate and symmetric vergence responses were however observed in the combined version-vergence- and reading task. In the reading task all subjects achieved binocular fixation through an appropriate vergence response, including those subjects who showed insufficient vergence responses in the pure vergence task. It was suggested that the improved accuracy may be due to facilitation by versional eye movements. Other factors might be a more precise accommodative response where the properties of the stimulus may play a role, i.e. the complex stimulus of words in text versus simple stimulus such as LED's or dots used in experimental studies. In a study that specifically analyzed the post-saccadic vergence drift in reading it was found that the vergence response was equally distributed between the eyes (Vernet & Kapoula, 2009). It thus appears that, even though effects of eye dominance may be visible in motor function, these effects are more difficult to detect in reading eye movements due to smaller magnitudes.

A third explanation to the weak relation between eye dominance and performance in the present study may be related to the viewing condition and perceptual factors. A study applying visual search tasks found no differences in recognition time or correct responses related to eye dominance when comparing monocular performance (Porac & Coren, 1979). However, when applying dichoptic presentation there was an asymmetry in recognition accuracy where the non-dominant eye performed inferior compared to not only dominant eye, but also compared to its monocular performance. Further experiments applying for example dichoptic presentation during reading may help assess if there are asymmetries in visual processing and recognition related to eye dominance.

## 5.3 EYE DOMINANCE UNDER BINOCULAR VIEWING CONDITIONS

In paper III eye dominance was explored under binocular viewing conditions using two principles; binocular sighting and monitoring of the binocular percept. The hole-in-the-card sighting test was used for reference. The main finding of the binocular sighting test (BST) was that a majority of subjects positioned to aim from a reference point, projection center, which did not coincide with one eye but rather with a point somewhere between the eyes. Furthermore, this behavior was correlated to an interocular difference in sensitivity to degraded visibility.

A two-step positioning was observed where the subjects initially positioned themselves to aim from a projection center approximately midway between the eyes. Shortly after that, the subject translated their positioning sideways to take a final position, where the projection center was repositioned towards either eye. A similar behavior was observed in a previous study that manipulated the visual feedback during a binocular alignment task (Barbeito, 1981). This seems to suggest that most subjects first attempted to aim from a reference point approximately midway between the eyes, presumably the egocenter. As observed in previous studies, the egocenter may have been located slightly closer to one eye (Barbeito, 1981; Porac & Coren, 1986; Sheedy & Fry, 1979) and thus possibly have had an effect on the subsequent positioning (Barbeito, 1981). Five subjects took a final position that made the line of sight of one eye coincide with the stimulus line, and thus appeared to disregard the input from one eye. A similar observation was made in a study of monocular preferences in binocular viewing where a minority of subject exclusively used one of the eyes (Purves & White, 1994).

The nearer object to be aligned appeared in physiologic diplopia. Presumably, the subject chose one of the diplopic images for alignment, similar to in the point-, or Porta test. With a strong eye dominance one diplopic image may have appeared markedly salient and thus more likely to be used for alignment. With less pronounced eye dominance, and more equally salient diplopic images, the decision may have been less obvious and more likely to be influenced by chance. Another factor that may have affected the subjects positioning is the perceived direction of the diplopic images. A displacement of the perceived visual direction of diplopic images has been noted in previous research (Rose & Blake, 1988). This effect occurred even if the images were separated by one degree or more which exceeds the disparities obtained in the present experiment. It was suggested that due to a perceptual mechanism that seeks to match and assign similar directions, the diplopic images are perceived to be closer than they are based on a purely retinotopic local sign.

With induced monocular blur, a significant correlation was found between the baseline projection center and the absolute change in projection center. The stronger the weighting of the baseline projection center towards one eye, the more monocular blur could be induced to the contralateral eye without affecting positioning. On the other hand, when inducing blur to the ipsilateral eye an immediate shift of projection center occurred. Francis and Harwood (Francis & Harwood, 1951), who measured the effect of neutral density filters in front of either eye, also found an approximate proportional relationship between reduced sensation in either eye and change of projection center.

It has been suggested that the change in projection center may be related to a change of position of the subject’s egocenter, or cyclopean eye (Erkelens, Muijs, & van Ee, 1996; Mansfield & Legge, 1996). This idea has been challenged with reference to the conventional theory of binocular visual direction and claiming that the cyclopean eye has a fixed position (Banks, Van Ee, & Backus, 1997; Mapp & Ono, 1999). Another concept that may be related to the behavior observed in the present experiment is ocular prevalence (Kommerell et al., 2003). Ocular prevalence is the unequal weighting of monocular views when judging visual directions of stereo objects and it occurs commonly in subjects with normal vision (Jaschinski & Schroth, 2008; Kromeier et al., 2006). In a study that measured the change in ocular prevalence as a neutral density was put in front of the eye with strongest prevalence found marked change in prevalence and perceived alignment of the stereo objects (Kommerell et al., 2003). This behavior resembles what has been observed in the present experiment. From a clinical perspective it was suggested that ocular prevalence may be due to a partial suppression that serves to disregard double images at disparities near the limits of Panum's fusional area (Kommerell et al., 2003). This might then help explain the interocular differences in sensitivity to blur and how it affected the projection center in the current experiment.

The experiment involving the Variable Angle Mirror Test (VAMT) also indicated the occurrence of a form of eye dominance. It showed both in the baseline response and in a correlation to interocular differences in blur sensitivity. Many subjects initially found it difficult to notice the images of the hinge. At baseline measure 28% of the subjects did not show a preference. This is in fair agreement with the finding in the original experiment (Bjork, 1980). The measurement of inter ocular difference in sensitivity to blur did however appear to help in discriminating weaker forms of dominance; and thus reducing the share of subjects that did not show a preference from 28 to 19%. Some subjects reported a perceived displacement of the image of the hinge. It was perceived to be located between the nose and the eye, instead of covering one eye. The mechanism behind this remains to be understood. However, it could possibly be related to the apparent displacement that may occur to diplopic non fused objects (Rose & Blake, 1988).

The correlation between BST and VAMT on total group level was weak. Interestingly though, a group of 14 subjects (44%) showed a complete agreement between the tests along with an almost complete agreement with the HICT. It appears that these subjects had a pronounced eye dominance that remained despite the differences in test conditions. While acknowledging the known difficulties of comparing results between different tests, it still appears that this share of subjects fits within the range (35-50%) that have been categorized as having a strong eye preference in previous research (Handa et al., 2005; Li et al., 2010; Purves & White, 1994; Valle-Inclán et al., 2008; Yang et al., 2010).

When relating the results of the experiments to the HICT the poorest agreement was found between the HICT and the BST. In the study of monocular preferences under binocular viewing only a moderate agreement was found with the Mile A-B-C test (Purves & White, 1994). In that study it was also observed that only a handful subjects exclusively selected one eye while the majority used both eyes to lesser or greater extent. This appears to agree with previous research where about 50% of subjects do not show a strong dominance (Handa et al., 2005; Li et al., 2010; Purves & White, 1994; Valle-Inclán et al., 2008; Yang et al., 2010). A subject with weaker dominance, who presumably values the monocular views more equal, is likely to show an alternating behavior (Kommerell et al., 2003) which may explain the poor overall agreement in the current study. When relating the results of the VAMT to HICT a moderate agreement was observed. The VAMT present a rather strong stimulus, the image of the face. As noted in the original experiment (Bjork, 1980), the face compels stronger attention than other objects may do. This aspect may explain the difficulty experienced by many subjects to initially notice the images of the hinge. If this is the case, this test may be more effective in identifying subjects with pronounced eye dominance and thus explain the stronger agreement with the HICT as compared to the BST.

## 5.4 THE EFFECT OF SPECTACLE TREATMENT IN PATIENTS WITH MTBI

In paper IV the effects of spectacle treatment on visual symptoms, binocular function and reading performance were evaluated in a group of patients with persisting symptoms after mild traumatic brain injury. The symptoms included what appeared to be diffuse vision-based symptoms. The Convergence Insufficiency Symptom Survey (CISS) (Borsting et al., 2003; Rouse et al., 2004) was used in order to estimate vision-based symptoms at near work and reading. The CISS has been used in previous studies to estimate visual symptoms in MTBI-patients at the sub-acute stage as well as in patients with long-standing symptoms (Capo-Aponte et al., 2012; Thiagarajan et al., 2014). The survey specifically targets near-work- and reading-related symptoms due to convergence insufficiency. However, since near work and reading requires the synchronized orchestration of several ocular motor functions; accommodation, vergence, version and gaze stabilization, a dysfunction in any of these are likely to result in an elevated symptom score. Furthermore, some of the survey items are not specific to vision related issues and thus other dysfunctions, such as an affected cognitive ability, e.g. concentration and memory issues, may affect the symptom score. Before treatment all patients scored well above the score (≥21) that is considered the limit for being visually symptomatic (mean 37.9±7.3). The symptom profile showed that specific visual symptoms did not stand out. Instead, other symptoms were more pronounced; i.e. diffuse symptoms of eye strain (eyes feel tired, eyes feel uncomfortable, headache), cognitively related symptoms (lose concentration, trouble remembering), and reading-related symptoms (feel read slowly, lose place while reading, have to re-read). This seems to reflect the overall unspecific symptom image which is common for these patients. Furthermore, it appears that the symptoms tend to be expressed in a functional context, in this case as reading-related symptoms.

The optometric examination showed a good visual acuity in all patients. This finding further emphasizes that visual acuity alone does not serve as a good indicator of the integrity of visual function in these patients. Accommodative- and vergence-related dysfunctions were found in all patients and spectacles were prescribed to balance for these issues. Five patients were examined and prescribed spectacles less than 12 months post injury. It may be considered that any spontaneous recovery should be awaited for 6-12 months, however there is clinical experience suggesting that treatment should start as early as possible in the rehabilitation process (Scheiman & Wick, 2014).

At the follow up examination four patients showed a considerable reduction in symptom score whereof two reached a score indicating them to be asymptomatic (≤21). In these patients the optometric examination showed an improvement in at least one clinical measure. The improvements were however modest and did not reach the expected span for most of the patients. Three patients neither showed any improvement in clinical measures nor a significant reduction in symptoms.

The overall symptom profile indicated a general reduction suggesting that wearing spectacles at near work reduced some of the immediate strain. The main exception was the symptom of reading feeling slow, which basically remained unchanged. This observation further points out reading-related issues as a key symptom. As with judgment of other self-reported symptoms there are various aspects to consider. For example there are indications that the symptom reporting may be biased by an apparent misperception of pre-injury functioning, i.e. that pre-injury issues are underestimated (Lange, Iverson, & Rose, 2010). This highlights the need for interdisciplinary cooperation in the judgement of symptoms and planning of interventions.

The evaluation of reading performance at the first examination showed reading to be 20.5% slower than a reference group of healthy subjects reading the same IReST texts at the same experimental conditions (J. Johansson et al., 2014b). After treatment it was still 8.4% slower. This observation appears to support the symptom of reading slowly. It should be noted that no active treatment such as vision therapy was prescribed in this study. Apart from vergence and accommodative dysfunctions, the versional eye movements, i.e. fixations, saccades and smooth pursuit, may be affected following TBI and causing less efficient reading performance (Ciuffreda et al., 2006; Ciuffreda et al., 2007; Han, Ciuffreda, & Kapoor, 2004; Thiagarajan et al., 2014). Versional eye movements are not targeted with spectacle treatment alone.

Four patients increased their reading speed after treatment while two patients showed a decrease. Of the four patients who increased their reading speed, two were still scoring as visually symptomatic. One of the patients who showed a significant reduction in symptoms appeared to read slower at the follow up examination. These inconsistent observations indicate some of the challenges associated with using reading performance as a clinical measure. One factor being the adaptability of the patient’s visual system, i.e. the ability to exert extra effort and maintain performance, but at the cost of visual discomfort (D. J. Grisham et al., 1993; Rosenfield et al., 2012). The development of methods to use extended continuous reading for assessment of reading perseverance, and monitoring of performance of over time, may be a way of targeting this. In patients experiencing double vision the visual system may adapt through suppression of one eye. This has been observed for example in patients with convergence insufficiency when switching to a near task (van Leeuwen et al., 1999). Suppression of one eye may allow for maintaining single vision and thus avoiding a disruption of the reading process. However, there are indications that one-eyed reading may be subject to reduced reading efficiency (Jainta et al., 2014; J. Johansson et al., 2014a). The maintenance of binocularity while reading thus appears as an aspect to control for in future experiments.

The comparison of monocular and binocular reading performance indicated that all patients read faster with two eyes than with one. The binocular advantage in reading speed was on average 11.9 % which is generally higher than expected in healthy subjects (up to 5%) according to previous research (J. Johansson et al., 2014b; Kanonidou et al., 2010; Robinson, 1951). Furthermore, the estimation of reading comprehension indicated poorer performance at monocular reading with on average 43% correct answered control questions compared to 90% at binocular reading. In previous studies involving healthy subjects, the reading comprehension appeared unaffected at monocular reading (J. Johansson et al., 2014a, 2014b). These observations seem to indicate that binocular function provided a marked advantage, even when reading text of good legibility. If this is the case, then an extension of this may be that one of the aims for optometric intervention should be to optimize binocular function, where appropriate, at an early stage post injury.

Finally, due to the complexity of the reading process several different mechanisms may have strong impact on the performance. These mechanisms may include cognitive factors such as fatigue, concentration, and ability to process visual information (B. Johansson et al., 2009; Raymond et al., 1996). There may be also an impaired ocular motor function affecting the efficiency in reading eye movements (Ciuffreda et al., 2006; Han et al., 2004; Thiagarajan et al., 2014). This suggests that it may be necessary to consider restoring treatments, such as ocular motor rehabilitation, which has previously been shown to be effective in improving performance and symptoms (Thiagarajan & Ciuffreda, 2013, 2014; Thiagarajan et al., 2014; Yadav, Thiagarajan, & Ciuffreda, 2014) and, where appropriate, to combine this with visual processing rehabilitation (Raymond et al., 1996) and occupational therapy interventions (Radomski et al., 2009).

# 6 CONCLUSIONS

The contribution of binocularity was estimated in healthy subjects and in patients with persisting symptoms following MTBI. Secondly, the role of eye dominance in reading and the occurrence of graded eye dominance under true binocular viewing conditions were evaluated. The project concluded with an evaluation of the effect of spectacle treatment on visual function, symptoms and reading performance in patients with MTBI. Some of the main findings are listed:

- Monocular and binocular reading performance differed marginally when text was presented at high contrast. On the other hand, the binocular reading performance was superior to monocular at reduced contrast. The findings parallel the binocular summation literature and suggest that binocularity contributes to the robustness of reading performance.
- The magnitude of the binocular advantage in reading was generally greater in patients than in healthy subjects. This seems to indicate that patients are more reliant on the enhancement of visual input provided by binocular vision.
- The mean fixation duration was significantly prolonged at monocular reading. Reduced contrast further prolonged the duration and an interaction effect between viewing condition and contrast level was found. These findings indicate that the denial of a binocular percept affected the reading process.
- Reading comprehension was robust to viewing condition and contrast in the healthy subjects. However, in the patients the monocular reading led to markedly less correct answers indicating an interference with comprehension.
- Monocular reading performance was generally equal with no clear relation to eye dominance. These findings appear to agree with previous studies involving subjects with normal vision.
- The eye dominance experiments indicated forms of graded eye dominance at binocular viewing conditions. The overall agreement with a sighting test was poor. Only a subset of subjects showed an almost complete agreement between tests. These findings may in part explain the difficulty to relate eye dominance and performance.
- Spectacle treatment provided a marked reduction in near vision symptoms in some of the patients. The symptom reduction was associated with modest improvements in visual function. These findings may indicate the need to consider restoring treatments.
- The relation between symptom reduction and improved reading performance after spectacle treatment was inconsistent. This finding highlights the challenge of using reading performance as a clinical measure and indicate the need for further development of the evaluation methods.

# 7 FUTURE PERSPECTIVES

In this project some striking observations regarding the contribution of binocularity to reading performance was made. The main difference in eye movements was an increase in mean fixation duration but also some changes in saccade length. To develop the understanding for the mechanisms behind this, further research will be required. Some potential future projects may aim at discriminating whether it is mainly the motor aspects, lexical aspects or an interaction that causes the reduced reading efficiency. This will require the development of models for detailed analysis of reading eye movements versus the lexical content. Another potential project is the development of texts and models to evaluate extended continuous reading. This can help target the challenges related to the patients reading goal and effects of visual adaptability.

The project concluded with a case study involving patients with persisting symptoms after MTBI. In this patient sample there were clear findings of visual symptoms, visual function anomalies and reading-related issues. However, some matters for consideration emerged during the study and in clinical observations paralleling the study work:

The first example refers to the patient selection. A careful review of medical records is required to determine the severity of brain injury and take into consideration other factors that may affect the patient's current health status. Due to the complexity of this determination a considerable rate of fall-outs may be expected. To account for this a sufficient time frame will be required for future projects.

The second example refers to the actual incidence and etiology of visual function issues in in patients with persisting problems after TBI. There appear to be evidence that visual function issues in the sub-acute stage are significantly more common than in the general clinical population (Alvarez et al., 2012; Brahm et al., 2009; Capo-Aponte et al., 2012; Ciuffreda et al., 2007; Goodrich et al., 2013; Stelmack et al., 2009). However, the incidence of long-term visual function issues is less obvious. The limited number of studies that have addressed this appear to frequently have encountered the challenges also observed in the current case-study; mainly a great variability in etiology and time since injury. This complicates the analysis and understanding of what issues are effects of the actual injury. Interdisciplinary prospective studies will be required where the various aspects of brain injury can be controlled for

A third example is how the potential of remaining brain plasticity should be utilized in terms of visual function. There is research in support of that MTBI-patients can benefit from vision therapy (Thiagarajan & Ciuffreda, 2013, 2014; Thiagarajan et al., 2014; Yadav et al., 2014). The spectacle treatment in the current study resulted in modest improvements in visual function. However, pilot testing of vision therapy showed some striking improvements along with reduced symptoms. Clinical studies can help improve the understanding of which patients will benefit from vision therapy and the sustainability of restored visual functions. Furthermore, patient reports of general improvements in the ability to deal with activities of daily life following vision therapy raise some interesting questions on the interaction with cognitive functions.

Based on these examples there appear to be interesting research opportunities with the prospect for some fairly straightforward clinical applications. Visual function assessment, including reading performance, appears as a promising contributor in this research due to the opportunities for objective measures mirroring brain function in a functional context.

# 8 ACKNOWLEDGEMENTS

I wish to express my sincere gratitude to everyone who has helped, supported and encouraged me during the time of the thesis work. In particular I would like to thank:

Professor Jan Ygge, head of MBC and also my co-author and co-supervisor; for the opportunity to join the team and get access to the laboratory and research facilities, for constructive discussions, and for sharing his ideas and extensive knowledge.

Associate professor Tony Pansell, my principal supervisor and co-author; for the continuous support during this project; for his guidance, patience, open mind and immense knowledge. Our countless spontaneous discussions have meant a lot and been a source for great inspiration.

Dr Gustaf Öqvist Seimyr, my co-supervisor and co-author; for his continuous support, for fruitful comments and discussions and for sharing his immense knowledge. His insightful advice has been key for the thesis work and is much appreciated.

Professor emeritus Gunnar Lennerstrand for the encouragement, contribution to discussions and sharing of ideas.

Dr Catharina Nygren de Boussard, my co-author; for a most fruitful cooperation, for suggestions and for educating on the many complex aspects of brain injury. I look forward to the projects to come.

Märta Berthold Lindstedt, for her clinical mentorship and the opportunity to closely follow the work of her team. It has been a great inspiration during the thesis work and for projects to come.

Professor Roberto Bolzani for advice in statistical matters and constructive discussions.

Dr Inger Skolin, my mentor, for her encouragement and advice.

University secretaries Mia Pettersson and Ulla-Britt Schützler-Petersson for their indispensable support in practical matters and for arranging all the nice activities during these years.

My supportive colleagues at MBC research lab: Dr Agneta Rydberg, Andrea Strandberg, Annika Pettersson, Dr Bing Zhang, Ida Bergman, Dr Kerstin Hellgren, Dr Lena Jacobsson, Dr Mattias Nilsson, Dr Monica Olsson, Dr Saber Abdi, Solveig Jonsson, Susanne Glimne and Dr Ulrika Sverkersten. Thanks for the discussions, suggestions and all the fun we have had. You make this a great work place.

All colleagues at Rehabilitation Medicine Stockholm, Huddinge, for sharing their knowledge and experience. Their creativity, drive and interest for vision is a great source for inspiration.

I would like to thank my parents, Rolf and Christina Johansson; for the encouragement, support in practical matters and for fantastic, energizing dinners. And my brother; Lars Johansson, for his support and for sharing his knowledge in medicine.

Finally, I would like to thank my wonderful wife Ann-Marie and daughter Johanna; for the encouragement, support and for letting me pursue this journey despite that we had to be apart for so much time. I could not have made it without you.

Important financial contributions were made by:

Sigvard och Marianne Bernadottes Forskningsstiftelse för barnögonvård
Karin Sandqvists stiftelse

# 9 REFERENCES

Alexander, M. P. (1995). Mild traumatic brain injury: pathophysiology, natural history, and clinical management. Neurology, 45(7), 1253-1260.

Altpeter, E. K., Marx, T., Nguyen, N. X., Naumann, A., & Trauzettel-Klosinski, S. (2015). Measurement of reading speed with standardized texts: a comparison of single sentences and paragraphs. Graefes Arch Clin Exp Ophthalmol.

Alvarez, T. L., Kim, E. H., Vicci, V. R., Dhar, S. K., Biswal, B. B., & Barrett, A. M. (2012). Concurrent vision dysfunctions in convergence insufficiency with traumatic brain injury. Optom Vis Sci, 89(12), 1740-1751.

APA. (1994). Diagnostic and Statistical Manual of Mental Disorders, Fourth Edition. Washington, DC: American Psychiatric Association.

Banks, M. S., Van Ee, R., & Backus, B. T. (1997). The computation of binocular visual direction: a re-examination of Mansfield and Legge (1996). Vision Res, 37(12), 1605-1613.

Banton, T., & Levi, D. M. (1991). Binocular summation in vernier acuity. J Opt Soc Am A, 8(4), 673-680.

Bárány, E. (1946). A theory of binocular visual acuity and an analysis of the variability of visual acuity. Acta Ophthalmol (Copenh), 24(1), 63-92.

Barbeito, R. (1981). Sighting dominance: an explanation based on the processing of visual direction in tests of sighting dominance. Vision Res, 21(6), 855-860.

Barbeito, R., Levi, D., Klein, S., Loshin, D., & Ono, H. (1985). Stereo-deficients and stereoblinds cannot make utrocular discriminations. Vision Res, 25(9), 1345-1348.

Bearse, M. A., Jr., & Freeman, R. D. (1994). Binocular summation in orientation discrimination depends on stimulus contrast and duration. Vision Res, 34(1), 19-29.

Bjork, A. (1980). The variable angle-mirror, a new tool for the study of ocular dominance and eye fixation. Acta Ophthalmol (Copenhagen), 58(2), 202-209.

Blake, R., Sloane, M., & Fox, R. (1981). Further developments in binocular summation. Percept Psychophys, 30(3), 266-276.

Blythe, H. I., Liversedge, S. P., Joseph, H. S., White, S. J., Findlay, J. M., & Rayner, K. (2006). The binocular coordination of eye movements during reading in children and adults. Vision Res, 46(22), 3898-3908.

Boake, C., McCauley, S. R., Levin, H. S., Pedroza, C., Contant, C. F., Song, J. X., Song, J. X., Brown, S. A., Goodman, H., Brundage, S. I. & Diaz-Marchan, P. J. (2005). Diagnostic criteria for postconcussional syndrome after mild to moderate traumatic brain injury. J Neuropsychiatry Clin Neurosci, 17(3), 350-356.

Bohnen, N., Twijnstra, A., & Jolles, J. (1992). Post-traumatic and emotional symptoms in different subgroups of patients with mild head injury. Brain Inj, 6(6), 481-487.

Borsting, E. J., Rouse, M. W., Mitchell, G. L., Scheiman, M., Cotter, S. A., Cooper, J., Kulp, M. T., London, R., Convergence Insufficiency Treatment Trial, Group. (2003). Validity and reliability of the revised convergence insufficiency symptom survey in children aged 9 to 18 years. Optom Vis Sci, 80(12), 832-838.

Brahm, K. D., Wilgenburg, H. M., Kirby, J., Ingalla, S., Chang, C. Y., & Goodrich, G. L. (2009). Visual impairment and dysfunction in combat-injured servicemembers with traumatic brain injury. Optom Vis Sci, 86(7), 817-825.

Campbell, F. W., & Green, D. G. (1965). Monocular versus binocular visual acuity. Nature, 208(5006), 191-192.

Capo-Aponte, J. E., Urosevich, T. G., Temme, L. A., Tarbett, A. K., & Sanghera, N. K. (2012). Visual dysfunctions and symptoms during the subacute stage of blast-induced mild traumatic brain injury. Mil Med, 177(7), 804-813.

Carroll, L. J., Cassidy, J. D., Cancelliere, C., Cote, P., Hincapie, C. A., Kristman, V. L., Holm, L. W., Borg, J., Nygren-de Boussard, C. & Hartvigsen, J. (2014). Systematic review of the prognosis after mild traumatic brain injury in adults: cognitive, psychiatric, and mortality outcomes: results of the International Collaboration on Mild Traumatic Brain Injury Prognosis. Arch Phys Med Rehabil, 95(3 Suppl), S152-173.

Carroll, L. J., Cassidy, J. D., Holm, L., Kraus, J., Coronado, V. G., & Injury, W. H. O. Collaborating Centre Task Force on Mild Traumatic Brain Injury. (2004). Methodological issues and research recommendations for mild traumatic brain injury: the WHO Collaborating Centre Task Force on Mild Traumatic Brain Injury. J Rehabil Med(43 Suppl), 113-125.

Cassidy, J. D., Cancelliere, C., Carroll, L. J., Cote, P., Hincapie, C. A., Holm, L. W., Hartvigsen, J., Donovan, J., Nygren-de Boussard, C., Kristman, V. L. & Borg, J. (2014). Systematic review of self-reported prognosis in adults after mild traumatic brain injury: results of the International Collaboration on Mild Traumatic Brain Injury Prognosis. Arch Phys Med Rehabil, 95(3 Suppl), S132-151.

Cassidy, J. D., Carroll, L. J., Peloso, P. M., Borg, J., von Holst, H., Holm, L., Kraus, J., Coronado, V. G., W. H. O. Collaborating Centre Task Force on Mild Traumatic Brain Injury (2004). Incidence, risk factors and prevention of mild traumatic brain injury: results of the WHO Collaborating Centre Task Force on Mild Traumatic Brain Injury. J Rehabil Med(43 Suppl), 28-60.

Castelhano, M. S., & Muter, P. (2001). Optimizing the reading of electronic text using rapid serial visual presentation. Behaviour & Information Technology, *20*(4), 237-247.

Chan, R. C. (2001). Base rate of post-concussion symptoms among normal people and its neuropsychological correlates. Clin Rehabil, 15(3), 266-273.

Charnwood, L. (1949). Observations on ocular dominance. Optician(118), 85-96.

Ciuffreda, K. J., Han, Y., Kapoor, N., & Ficarra, A. P. (2006). Oculomotor rehabilitation for reading in acquired brain injury. NeuroRehabilitation, 21(1), 9-21.

Ciuffreda, K. J., Kapoor, N., Rutner, D., Suchoff, I. B., Han, M. E., & Craig, S. (2007). Occurrence of oculomotor dysfunctions in acquired brain injury: a retrospective analysis. Optometry, 78(4), 155-161.

Collewijn, H., Erkelens, C. J., & Steinman, R. M. (1988). Binocular co-ordination of human horizontal saccadic eye movements. J Physiol, 404, 157-182.

Coren, S., & Kaplan, C. P. (1973). Patterns of ocular dominance. Am J Optom Arch Am Acad Optom, 50(4), 283-292.

Dean, P. J., O'Neill, D., & Sterr, A. (2012). Post-concussion syndrome: prevalence after mild traumatic brain injury in comparison with a sample without head injury. Brain Inj, 26(1), 14-26.

Ding, J., & Sperling, G. (2006). A gain-control theory of binocular combination. Proc Natl Acad Sci U S A, 103(4), 1141-1146.

Durand, A. C., & Gould, G. M. (1910). A method of determining ocular dominance. Journal of the American Medical Association(55), 369-370.

Dysli, M., Vogel, N., & Abegg, M. (2014). Reading performance is not affected by a prism induced increase of horizontal and vertical vergence demand. Front Hum Neurosci, 8, 431.

Ehrenstein, W. H., Arnold-Schulz-Gahmen, B. E., & Jaschinski, W. (2005). Eye preference within the context of binocular functions. Graefes Arch Clin Exp Ophthalmol, 243(9), 926-932.

Erkelens, C. J., Muijs, A. J., & van Ee, R. (1996). Binocular alignment in different depth planes. Vision Res, 36(14), 2141-2147.

Evans, B. J. (2007). Monovision: a review. Ophthalmic Physiol Opt, 27(5), 417-439.

Evans, R. W. (1992). The postconcussion syndrome and the sequelae of mild head injury. Neurol Clin, 10(4), 815-847.

Fisher, S. K., Ciuffreda, K. J., Levine, S., & Wolf-Kelly, K. S. (1987). Tonic adaptation in symptomatic and asymptomatic subjects. Am J Optom Physiol Opt, 64(5), 333-343.

Flax, N. (1970). Problems in relating visual function to reading disorder. Am J Optom Arch Am Acad Optom, 47(5), 366-372.

Francis, J. L., & Harwood, K. A. (1951). The variation of the projection centre with differential stimulus and its relation to ocular dominance. Paper presented at the Transactions of the International Optical Congress, British Optical Association, London.

Frisen, L., & Lindblom, B. (1988). Binocular summation in humans: evidence for a hierarchic model. J Physiol, 402, 773-782.

Goodrich, G. L., Flyg, H. M., Kirby, J. E., Chang, C. Y., & Martinsen, G. L. (2013). Mechanisms of TBI and visual consequences in military and veteran populations. Optom Vis Sci, 90(2), 105-112.

Grabow, J. D., Offord, K. P., & Rieder, M. E. (1984). The cost of head trauma in Olmsted County, Minnesota, 1970-74. Am J Public Health, 74(7), 710-712.

Green, W., Ciuffreda, K. J., Thiagarajan, P., Szymanowicz, D., Ludlam, D. P., & Kapoor, N. (2010). Accommodation in mild traumatic brain injury. J Rehabil Res Dev, 47(3), 183-199.

Greiffenstein, M. F. (2009). Clinical myths of forensic neuropsychology. Clin Neuropsychol, 23(2), 286-296.

Grisham, D. J., Sheppard, M. M., & Tran, W. U. (1993). Visual symptoms and reading performance. Optometry and Vision Science, 70(5), 384-391.

Grisham, J. D., & Simons, H. D. (1986). Refractive error and the reading process: a literature analysis. J Am Optom Assoc, 57(1), 44-55.

Grosvenor, T. (1977). Are visual anomalies related to reading ability? J Am Optom Assoc, 48(4), 510-517.

Guralnik, J. M., Branch, L. G., Cummings, S. R., & Curb, J. D. (1989). Physical performance measures in aging research. J Gerontol, 44(5), M141-146.

Han, Y., Ciuffreda, K. J., & Kapoor, N. (2004). Reading-related oculomotor testing and training protocols for acquired brain injury in humans. Brain Res Brain Res Protoc, 14(1), 1-12.

Han, Y., Seideman, M., & Lennerstrand, G. (1995). Dynamics of accommodative vergence movements controlled by the dominant and non-dominant eye. Acta Ophthalmol Scand, 73(4), 319-324.

Handa, T., Mukuno, K., Uozato, H., Niida, T., Shoji, N., & Shimizu, K. (2004). Effects of dominant and nondominant eyes in binocular rivalry. Optometry and Vision Science, 81(5), 377-383.

Handa, T., Shimizu, K., Mukuno, K., Kawamorita, T., & Uozato, H. (2005). Effects of ocular dominance on binocular summation after monocular reading adds. J Cataract Refract Surg, 31(8), 1588-1592.

Handa, T., Shimizu, K., Uozato, H., Shoji, N., & Ishikawa, H. (2012). A new method for quantifying ocular dominance using the balancing technique. Am Orthopt J, 62, 77-86.

Hartvigsen, J., Boyle, E., Cassidy, J. D., & Carroll, L. J. (2014). Mild traumatic brain injury after motor vehicle collisions: what are the symptoms and who treats them? A population-based 1-year inception cohort study. Arch Phys Med Rehabil, 95(3 Suppl), S286-294.

Hazel, C. A., Petre, K. L., Armstrong, R. A., Benson, M. T., & Frost, N. A. (2000). Visual function and subjective quality of life compared in subjects with acquired macular disease. Invest Ophthalmol Vis Sci, 41(6), 1309-1315.

Heller, D., & Radach, R. (Eds.). (1999). Eye movements in reading: are two eyes better than one? New York: Plenum Press.

Heravian, J. S., Jenkins, T. C., & Douthwaite, W. A. (1990). Binocular summation in visually evoked responses and visual acuity. Ophthalmic Physiol Opt, 10(3), 257-261.

Hokoda, S. C. (1985). General binocular dysfunctions in an urban optometry clinic. J Am Optom Assoc, 56(7), 560-562.

Hubel, D. H., & Wiesel, T. N. (1959). Receptive fields of single neurones in the cat's striate cortex. J Physiol, 148, 574-591.

Hubel, D. H., & Wiesel, T. N. (1962). Receptive fields, binocular interaction and functional architecture in the cat's visual cortex. J Physiol, 160, 106-154.

Humphiss, D. (1969). The measurement of sensory ocular dominance and its relation to personality. Am J Optom Arch Am Acad Optom, 46(8), 603-616.

Hyder, A. A., Wunderlich, C. A., Puvanachandra, P., Gururaj, G., & Kobusingye, O. C. (2007). The impact of traumatic brain injuries: a global perspective. NeuroRehabilitation, 22(5), 341-353.

Jackson, M. D., & McClelland, L. (1979). Processing determinants of reading speed. *J Exp Psychol Gen, 108*(2), 151-181.

Jainta, S., Blythe, H. I., & Liversedge, S. P. (2014). Binocular advantages in reading. Curr Biol, 24(5), 526-530.

Jainta, S., Dehnert, A., Heinrich, S. P., & Jaschinski, W. (2011). Binocular coordination during reading of blurred and nonblurred text. Invest Ophthalmol Vis Sci, 52(13), 9416-9424.

Jainta, S., Hoormann, J., Kloke, W. B., & Jaschinski, W. (2010). Binocularity during reading fixations: Properties of the minimum fixation disparity. Vision Res, 50(18), 1775-1785.

Jainta, S., & Jaschinski, W. (2012). Individual differences in binocular coordination are uncovered by directly comparing monocular and binocular reading conditions. Invest Ophthalmol Vis Sci, 53(9), 5762-5769.

Jaschinski, W., & Schroth, V. (2008). Ocular prevalence: difference between crossed and uncrossed disparities of stereo objects. Strabismus, 16(4), 159-164.

Johansson, B., Berglund, P., & Ronnback, L. (2009). Mental fatigue and impaired information processing after mild and moderate traumatic brain injury. Brain Inj, 23(13-14), 1027-1040.

Johansson, J., Pansell, T., Ygge, J., & Seimyr, G. O. (2014a). The effect of contrast on monocular versus binocular reading performance. J Vis, 14(5), 8.

Johansson, J., Pansell, T., Ygge, J., & Seimyr, G. O. (2014b). Monocular and binocular reading performance in subjects with normal binocular vision. Clin Exp Optom, 97(4), 341-348.

Jones, R. K., & Lee, D. N. (1981). Why two eyes are better than one: the two views of binocular vision. J Exp Psychol Hum Percept Perform, 7(1), 30-40.

Jordan, T. R., McGowan, V. A., & Paterson, K. B. (2012). Reading with a filtered fovea: the influence of visual quality at the point of fixation during reading. Psychon Bull Rev, 19(6), 1078-1084.

Juhasz, B. J., Liversedge, S. P., White, S. J., & Rayner, K. (2006). Binocular coordination of the eyes during reading: word frequency and case alternation affect fixation duration but not fixation disparity. Q J Exp Psychol (Hove), 59(9), 1614-1625.

Kanonidou, E., Proudlock, F. A., & Gottlob, I. (2010). Reading strategies in mild to moderate strabismic amblyopia: an eye movement investigation. Invest Ophthalmol Vis Sci, 51(7), 3502-3508.

Kawata, H., & Ohtsuka, K. (2001). Dynamic asymmetries in convergence eye movements under natural viewing conditions. Jpn J Ophthalmol, 45(5), 437-444.

King, N. S., Crawford, S., Wenden, F. J., Moss, N. E., & Wade, D. T. (1995). The Rivermead Post Concussion Symptoms Questionnaire: a measure of symptoms commonly experienced after head injury and its reliability. J Neurol, 242(9), 587-592.

Kommerell, G., Schmitt, C., Kromeier, M., & Bach, M. (2003). Ocular prevalence versus ocular dominance. Vision Res, 43(12), 1397-1403.

Kraus, J., Hsu, P., Schaffer, K., Vaca, F., Ayers, K., Kennedy, F., & Afifi, A. A. (2009). Preinjury factors and 3-month outcomes following emergency department diagnosis of mild traumatic brain injury. J Head Trauma Rehabil, 24(5), 344-354.

Kraus, J., Schaffer, K., Ayers, K., Stenehjem, J., Shen, H., & Afifi, A. A. (2005). Physical complaints, medical service use, and social and employment changes following mild traumatic brain injury: a 6-month longitudinal study. J Head Trauma Rehabil, 20(3), 239-256.

Kromeier, M., Heinrich, S. P., Bach, M., & Kommerell, G. (2006). Ocular prevalence and stereoacuity. Ophthalmic Physiol Opt, 26(1), 50-56.

Laborey, M., Masson, F., Ribereau-Gayon, R., Zongo, D., Salmi, L. R., & Lagarde, E. (2014). Specificity of postconcussion symptoms at 3 months after mild traumatic brain injury: results from a comparative cohort study. J Head Trauma Rehabil, 29(1), E28-36.

Lange, R. T., Iverson, G. L., & Rose, A. (2010). Post-concussion symptom reporting and the "good-old-days" bias following mild traumatic brain injury. Arch Clin Neuropsychol, 25(5), 442-450.

Lannsjo, M., af Geijerstam, J. L., Johansson, U., Bring, J., & Borg, J. (2009). Prevalence and structure of symptoms at 3 months after mild traumatic brain injury in a national cohort. Brain Inj, 23(3), 213-219.

Lara, F., Cacho, P., Garcia, A., & Megias, R. (2001). General binocular disorders: prevalence in a clinic population. Ophthalmic Physiol Opt, 21(1), 70-74.

Legge, G. E., Ahn, S. J., Klitz, T. S., & Luebker, A. (1997). Psychophysics of reading--XVI. The visual span in normal and low vision. Vision Res, 37(14), 1999-2010.

Legge, G. E., Parish, D. H., Luebker, A., & Wurm, L. H. (1990). Psychophysics of reading. XI. Comparing color contrast and luminance contrast. J Opt Soc Am A, 7(10), 2002-2010.

Legge, G. E., Pelli, D. G., Rubin, G. S., & Schleske, M. M. (1985). Psychophysics of reading--I. Normal vision. Vision Res, 25(2), 239-252.

Legge, G. E., Rubin, G. S., & Luebker, A. (1987). Psychophysics of reading--V. The role of contrast in normal vision. Vision Res, 27(7), 1165-1177.

Li, J., Lam, C. S., Yu, M., Hess, R. F., Chan, L. Y., Maehara, G., Woo, G. C. & Thompson, B. (2010). Quantifying sensory eye dominance in the normal visual system: a new technique and insights into variation across traditional tests. Invest Ophthalmol Vis Sci, 51(12), 6875-6881.

Liversedge, S. P., & Findlay, J. M. (2000). Saccadic eye movements and cognition. Trends Cogn Sci, 4(1), 6-14.

Liversedge, S. P., Rayner, K., White, S. J., Findlay, J. M., & McSorley, E. (2006). Binocular coordination of the eyes during reading. Curr Biol, 16(17), 1726-1729.

Liversedge, S. P., White, S. J., Findlay, J. M., & Rayner, K. (2006). Binocular coordination of eye movements during reading. Vision Res, 46(15), 2363-2374.

Magone, M. T., Kwon, E., & Shin, S. Y. (2014). Chronic visual dysfunction after blast-induced mild traumatic brain injury. J Rehabil Res Dev, 51(1), 71-80.

Mallet, R. F. J. (1966). A fixation disparity test for distance use. Optician(152), 1-4.

Mansfield, J. S., & Legge, G. E. (1996). The binocular computation of visual direction. Vision Res, 36(1), 27-41.

Mansfield, J. S., Legge, G. E., & Bane, M. C. (1996). Psychophysics of reading. XV: Font effects in normal and low vision. Invest Ophthalmol Vis Sci, 37(8), 1492-1501.

Mapp, A. P., & Ono, H. (1999). Wondering about the wandering cyclopean eye. Vision Res, 39(14), 2381-2386.

Mapp, A. P., Ono, H., & Barbeito, R. (2003). What does the dominant eye dominate? A brief and somewhat contentious review. Percept Psychophys, 65(2), 310-317.

Meares, S., Shores, E. A., Taylor, A. J., Batchelor, J., Bryant, R. A., Baguley, I. J., Chapman, J., Gurka, J. & Marosszeky, J. E. (2011). The prospective course of postconcussion syndrome: the role of mild traumatic brain injury. Neuropsychology, 25(4), 454-465.

Mild Traumatic Brain Injury Committee, A. C. o. R. M., Head Injury Interdisciplinary Special Interest Group. (1993). Definition of mild traumatic brain injury. J Head Trauma Rehabil, 8(3), 86–87.

Miles, W. R. (1929). Ocular dominance demonstrated by unconscious sighting., 12(2), 113-126.

Mills, L. (1928). Unilateral Sighting. Cal West Med, 28(2), 189-195.

Nelson Sheese, A. L., & Hammeke, T. A. (2014). Rehabilitation from postconcussion syndrome: nonpharmacological treatment. Prog Neurol Surg, 28, 149-160.

Nygren-de Boussard, C., Holm, L. W., Cancelliere, C., Godbolt, A. K., Boyle, E., Stalnacke, B. M., . Hincapie, C. A., Cassidy, J. D. & Borg, J. (2014). Nonsurgical interventions after mild traumatic brain injury: a systematic review. Results of the International Collaboration on Mild Traumatic Brain Injury Prognosis. Arch Phys Med Rehabil, 95(3 Suppl), S257-264.

O'Regan, J. K., & Levy-Schoen, A. (Eds.). (1987). Eye movement strategy and tactics in word recognition and reading. (Vol. 12): Hillsdale, NJ, Erlbaum.

Ogle, K. N. (1962). Ocular dominance and binocular retinal rivalry. In: Chapter 18. The Eye (ed. H. Davson). New York: Academic Press.

Ogle, K. N., Mussey, F., & Prangen, A. D. (1949). Fixation disparity and the fusional processes in binocular single vision. Am J Ophthalmol, 32(8), 1069-1087.

Oishi, A., Tobimatsu, S., Arakawa, K., Taniwaki, T., & Kira, J. (2005). Ocular dominancy in conjugate eye movements at reading distance. Neurosci Res, 52(3), 263-268.

Ono, H. (Ed.) (1991). Binocular visual directions of an object when seen as single or double. (Vol. 9). London: Macmillan.

Ono, H., & Barbeito, R. (1985). Utrocular discrimination is not sufficient for utrocular identification. Vision Res, 25(2), 289-299.

Ooi, T. L., & He, Z. J. (2001). Senory eye dominance. Optometry, 72(3), 168-177.

Öquist, G. (2006). Evaluating readability on mobile devices. (Doctoral thesis), Uppsala Universitet, Uppsala.

Panum, P. L. (1858). Physiologische Untersuchungen über das Sehen mit zwei Augen Kiel: Schwers.

Pardhan, S. (2003). Binocular recognition summation in the peripheral visual field: contrast and orientation dependence. Vision Res, 43(11), 1249-1255.

Ponsford, J., Cameron, P., Fitzgerald, M., Grant, M., Mikocka-Walus, A., & Schonberger, M. (2012). Predictors of postconcussive symptoms 3 months after mild traumatic brain injury. Neuropsychology, 26(3), 304-313.

Porac, C., & Coren, S. (1979). Monocular asymmetries in recognition after an eye movement: sighting dominance and dextrality. Percept Psychophys, 25(1), 55-59.

Porac, C., & Coren, S. (1986). Sighting dominance and egocentric localization. Vision Res, 26(10), 1709-1713.

Porcar, E., & Martinez-Palomera, A. (1997). Prevalence of general binocular dysfunctions in a population of university students. Optom Vis Sci, 74(2), 111-113.

Porta, J. B. (1593). De refractione optices parte: Libri novem. Naples: Carlinum & Pacem.

Purves, D., & White, L. E. (1994). Monocular preferences in binocular viewing. Proc Natl Acad Sci U S A, 91(18), 8339-8342.

Radomski, M. V., Davidson, L., Voydetich, D., & Erickson, M. W. (2009). Occupational therapy for service members with mild traumatic brain injury. Am J Occup Ther, 63(5), 646-655.

Rahman, T., & Muter, P. (1999). Designing an interface to optimize reading with small display windows. Hum Factors, 41(1), 106-117.

Raymond, M. J., Bennett, T. L., Malia, K. B., & Bewick, K. C. (1996). Rehabilitation of visual processing deficits following brain injury. NeuroRehabilitation, 6(3), 229-239.

Rayner, K. (1979). Eye guidance in reading: fixation locations within words. Perception, 8(1), 21-30.

Rayner, K. (1998). Eye movements in reading and information processing: 20 years of research. Psychol Bull, 124(3), 372-422.

Rayner, K., Inhoff, A. W., Morrison, R. E., Slowiaczek, M. L., & Bertera, J. H. (1981). Masking of foveal and parafoveal vision during eye fixations in reading. J Exp Psychol Hum Percept Perform, 7(1), 167-179.

Rice, M. L., Leske, D. A., Smestad, C. E., & Holmes, J. M. (2008). Results of ocular dominance testing depend on assessment method. J AAPOS, 12(4), 365-369.

Robinson, H. M. (1951). Factors related to monocular and binocular reading efficiency. Am J Optom Arch Am Acad Optom, 28(7), 337-346.

Rose, D., & Blake, R. (1988). Mislocalization of diplopic images. J Opt Soc Am A, 5(9), 1512-1521.

Rosenfield, M., Hue, J. E., Huang, R. R., & Bababekova, Y. (2012). The effects of induced oblique astigmatism on symptoms and reading performance while viewing a computer screen. Ophthalmic Physiol Opt, 32(2), 142-148.

Rouse, M. W., Borsting, E., Hyman, L., Hussein, M., Cotter, S. A., Flynn, M., Scheiman, M., Gallaway, M. & De Land, P. N. (1999). Frequency of convergence insufficiency among fifth and sixth graders. The Convergence Insufficiency and Reading Study (CIRS) group. Optom Vis Sci, 76(9), 643-649.

Rouse, M. W., Borsting, E. J., Mitchell, G. L., Scheiman, M., Cotter, S. A., Cooper, J., Kulp, M. T., London, R. Wensveen, J., Convergence Insufficiency Treatment Trial Group. (2004). Validity and reliability of the revised convergence insufficiency symptom survey in adults. Ophthalmic Physiol Opt, 24(5), 384-390.

Rubin, G. S. (2013). Measuring reading performance. Vision Res, 90, 43-51.

Ruff, R. (2005). Two decades of advances in understanding of mild traumatic brain injury. J Head Trauma Rehabil, 20(1), 5-18.

Scheiman, M., & Wick, B. (2014). Clinical Management of Binocular Vision: Heterophoric, Accommodative, and Eye Movement Disorders (4th ed. ed.). PA, USA: Lippincott Williams & Wilkins.

Schor, C., Landsman, L., & Erickson, P. (1987). Ocular Dominance and the Interocular Suppression of Blur in Monovision. American Journal of Optometry and Physiological Optics, 64(10), 723-730.

Sheedy, J. E., Bailey, I. L., Buri, M., & Bass, E. (1986). Binocular vs. monocular task performance. Am J Optom Physiol Opt, 63(10), 839-846.

Sheedy, J. E., & Fry, G. A. (1979). The perceived direction of the binocular image. Vision Res, 19(2), 201-211.

Simons, H. D. (1993). An analysis of the role of vision anomalies in reading interference. Optom Vis Sci, 70(5), 369-373.

Simons, H. D., & Gassler, P. A. (1988). Vision anomalies and reading skill: a meta-analysis of the literature. Am J Optom Physiol Opt, 65(11), 893-904.

Simons, H. D., & Grisham, J. D. (1987). Binocular anomalies and reading problems. J Am Optom Assoc, 58(7), 578-587.

Sridhar, D., & Bedell, H. E. (2011). Relative contributions of the two eyes to perceived egocentric visual direction in normal binocular vision. Vision Res, 51(9), 1075-1085.

Sridhar, D., & Bedell, H. E. (2012). Binocular retinal image differences influence eye-position signals for perceived visual direction. Vision Res, 62, 220-227.

Stein, J. F., & Fowler, S. (1982). Diagnosis of dyslexia by means of a new indicator of eye dominance. Br J Ophthalmol, 66(5), 332-336.

Steinman, S. B., Steinman, B. A., & Garzia, R. P. (2000). Foundations of Binocular Vision: A Clinical Perspective. New York: McGraw-Hill Companies.

Stelmack, J. A., Frith, T., Van Koevering, D., Rinne, S., & Stelmack, T. R. (2009). Visual function in patients followed at a Veterans Affairs polytrauma network site: an electronic medical record review. Optometry, 80(8), 419-424.

Suter, P. S., & Harvey, L. H. (Eds.). (2011). Vision Rehabilitation. Multidisciplinary Care of the Patient Following Brain Injury. Boca Raton, FL: CRC Press, Taylor & Francis Group.

Szymanowicz, D., Ciuffreda, K. J., Thiagarajan, P., Ludlam, D. P., Green, W., & Kapoor, N. (2012). Vergence in mild traumatic brain injury: a pilot study. J Rehabil Res Dev, 49(7), 1083-1100.

Tagliaferri, F., Compagnone, C., Korsic, M., Servadei, F., & Kraus, J. (2006). A systematic review of brain injury epidemiology in Europe. Acta Neurochir (Wien), 148(3), 255-268; discussion 268.

Teasdale, G., & Jennett, B. (1974). Assessment of coma and impaired consciousness. A practical scale. Lancet, 2(7872), 81-84.

Thiagarajan, P., & Ciuffreda, K. J. (2013). Effect of oculomotor rehabilitation on vergence responsivity in mild traumatic brain injury. J Rehabil Res Dev, 50(9), 1223-1240.

Thiagarajan, P., & Ciuffreda, K. J. (2014). Effect of oculomotor rehabilitation on accommodative responsivity in mild traumatic brain injury. J Rehabil Res Dev, 51(2), 175-191.

Thiagarajan, P., Ciuffreda, K. J., Capo-Aponte, J. E., Ludlam, D. P., & Kapoor, N. (2014). Oculomotor neurorehabilitation for reading in mild traumatic brain injury (mTBI): an integrative approach. NeuroRehabilitation, 34(1), 129-146.

Trauzettel-Klosinski, S., Dietz, K., & Group, I. R. S. (2012). Standardized assessment of reading performance: the New International Reading Speed Texts IReST. Invest Ophthalmol Vis Sci, 53(9), 5452-5461.

Valle-Inclán, F., Blanco, M. J., Soto, D., & Leirós, L. (2008). A new method to assess eye dominance. Psicológica(29), 55-64.

Walls, G. L. (1951). A theory of ocular dominance. AMA Arch Ophthalmol, 45(4), 387-412.

van Leeuwen, A. F., Westen, M. J., van der Steen, J., de Faber, J. T., & Collewijn, H. (1999). Gaze-shift dynamics in subjects with and without symptoms of convergence insufficiency: influence of monocular preference and the effect of training. Vision Res, 39(18), 3095-3107.

Vernet, M., & Kapoula, Z. (2009). Binocular motor coordination during saccades and fixations while reading: a magnitude and time analysis. J Vis, 9(7), 2.

Whittaker, S. G., & Lovie-Kitchin, J. (1993). Visual requirements for reading. Optom Vis Sci, 70(1), 54-65.

WHO. (1992). The ICD-10 Classification of Mental and Behavioural Disorders: Clinical Descriptions and Diagnostic Guidelines. Geneva, Switzerland: World Health Organization.

Wickens, C. D. (1992). Engineering psychology and human performance (2nd ed.). New York: HarperCollins Publishers Inc.

Wolffsohn, J. S., Bhogal, G., & Shah, S. (2011). Effect of uncorrected astigmatism on vision. J Cataract Refract Surg, 37(3), 454-460.

von Noorden, G., K., & Campos, E., C. (2002). Binocular vision and ocular motility : theory and management of strabismus (6th ed.). St. Louis, Missouri: Mosby, Inc.

Wong, J. L., Regennitter, R. P., & Barrios, F. (1994). Base rate and simulated symptoms of mild head injury among normals. Arch Clin Neuropsychol, 9(5), 411-425.

Woodman, W., Young, M., Kelly, K., Simoens, J., & Yolton, R. L. (1990). Effects of monocular occlusion on neural and motor response times for two-dimensional stimuli. Optom Vis Sci, 67(3), 169-178.

Yadav, N. K., Thiagarajan, P., & Ciuffreda, K. J. (2014). Effect of oculomotor vision rehabilitation on the visual-evoked potential and visual attention in mild traumatic brain injury. Brain Inj, 28(7), 922-929.

Yang, E., Blake, R., & McDonald, J. E., 2nd. (2010). A new interocular suppression technique for measuring sensory eye dominance. Invest Ophthalmol Vis Sci, 51(1), 588-593.

Yekta, A. A., Jenkins, T., & Pickwell, D. (1987). The clinical assessment of binocular vision before and after a working day. Ophthalmic Physiol Opt, 7(4), 349-352.

Zeri, F., De Luca, M., Spinelli, D., & Zoccolotti, P. (2011). Ocular dominance stability and reading skill: a controversial relationship. Optom Vis Sci, 88(11), 1353-1362.

Zlatkova, M. B., Anderson, R. S., & Ennis, F. A. (2001). Binocular summation for grating detection and resolution in foveal and peripheral vision. Vision Res, 41(24), 3093-3100.